



Research for a Life without Cancer



Single Plane Positioning Tracking Proton and Helium Pencil Beam Radiographs: Phantom Study

Alexander Pryanichnikov, PhD
The 6th Ion Imaging Workshop

27.10.2025

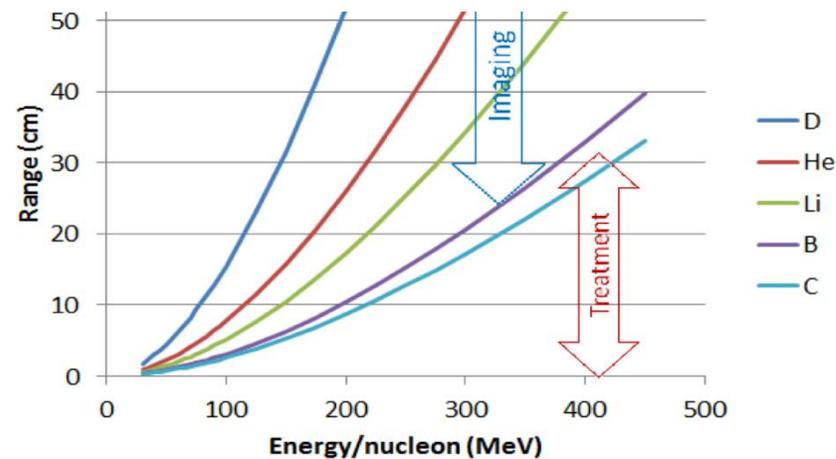
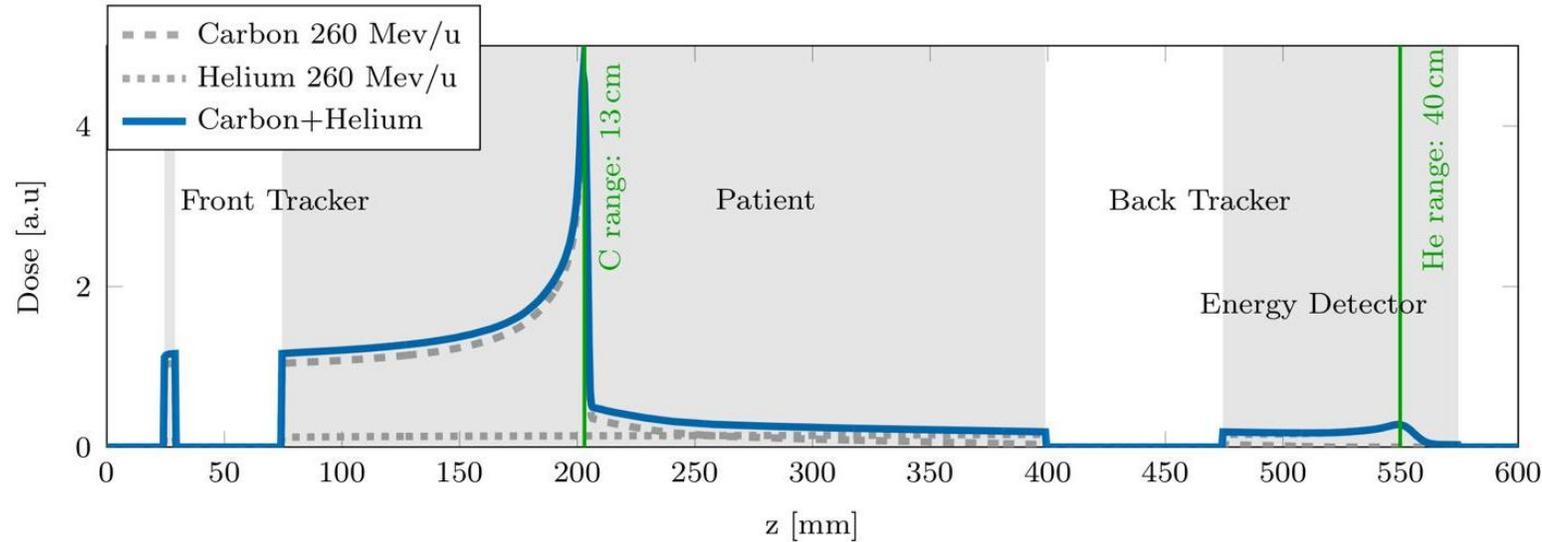
Agenda

1. HELIOS project
2. Simulation and treatment planning
3. Instrumentation
4. Experimental imaging: single tracker results
5. Overview of related projects



Motivation and the HELIOS project @DKFZ

- **HELIum Imaging Oncology Scanner**
- Use $^{12}\text{C}^{6+}$ for treatment and $^4\text{He}^{2+}$ for imaging (Graeff C *et al. Phys Med. 2018; 52:11*, Mazzucconi D *et al. Med Phys. 2018; 45:5234-5243*, Volz L *et al. Phys Med Biol. 2020; 65:055002*)
- Beam eye view of helium radiographs according to the carbon-helium treatment plan (Hardt JJ *et al. Phys Med Biol. 2024; 69(12)*)
- Use established technologies with minor modifications (Pryanichnikov AA *et al. Phys Med. 2025;133:104959*)



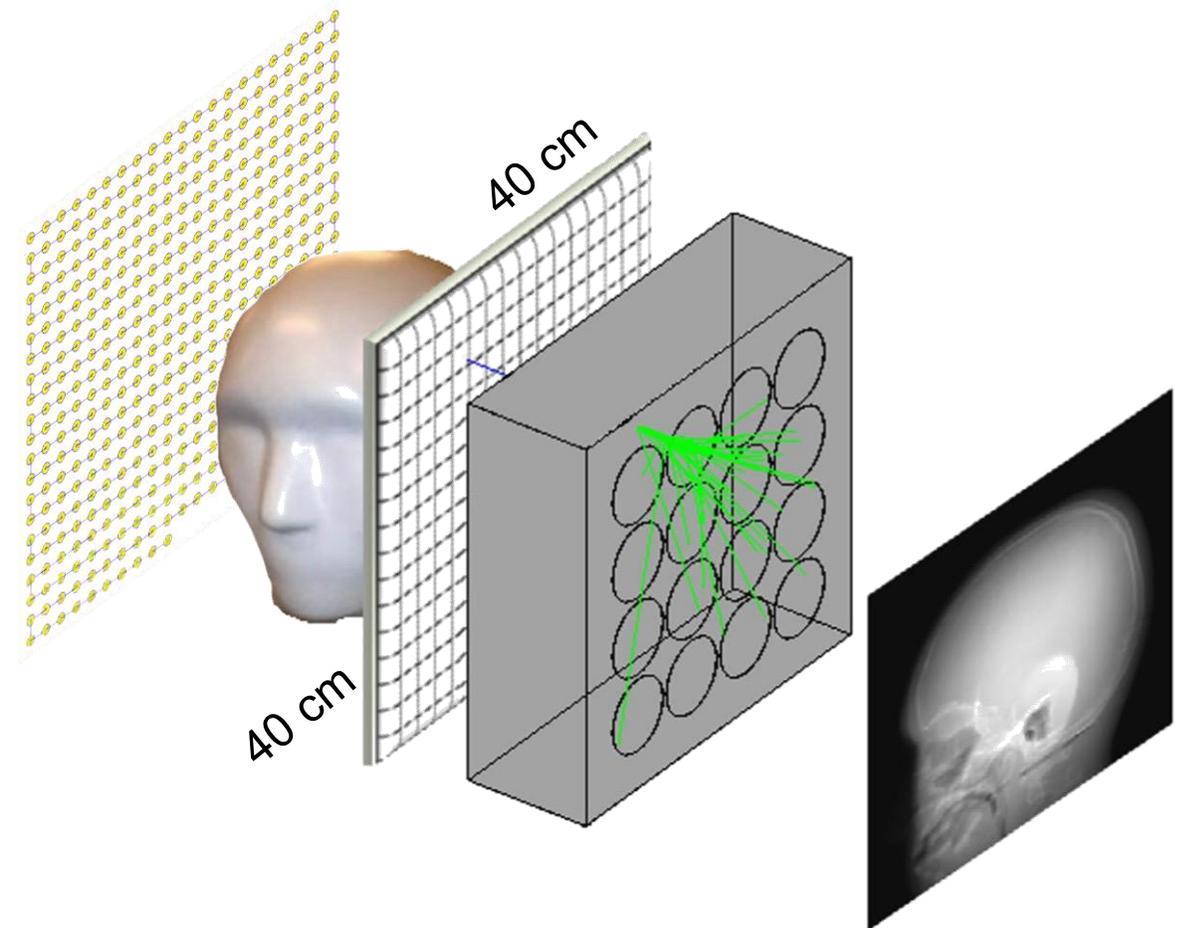
Imaging detector: principle

The classic particle imaging system requires:

- Beam position trackers;
- A calorimeter to measure residual energy;
- Reconstruction algorithms.

The single-tracker particle imaging system requires:

- A downstream beam position tracker;
- Beam position data from the delivery system;
- Precise knowledge of the room geometry;
- A calorimeter to measure residual energy;
- Reconstruction algorithms.



Simulation and reconstruction of radiographs I



Score phase space of **primary Helium** ions at tracker position



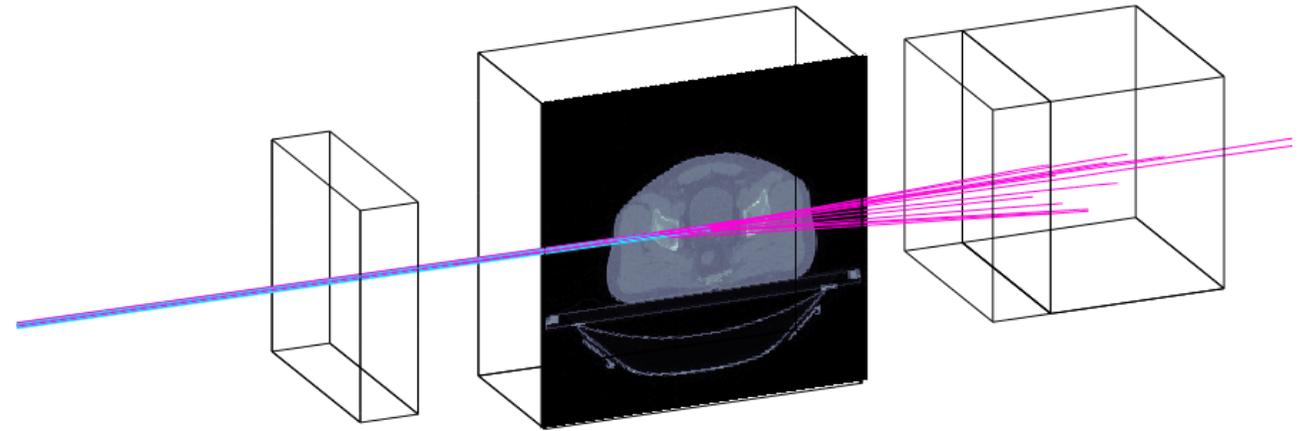
From initial/final energy calculate
WEPL = $R_{\text{Init}} - R_{\text{Final}}$



Reconstruct **particle path** and calculate intersection point with Isocenter plane



Calculate **mean WEPL** in each image pixel



Schematic setup of radiotherapy with a mixed ^{12}C (blue) and ^4He (pink) beam and the range detector

Simulation and reconstruction of radiographs II



Score phase space of **primary Helium** ions at tracker position



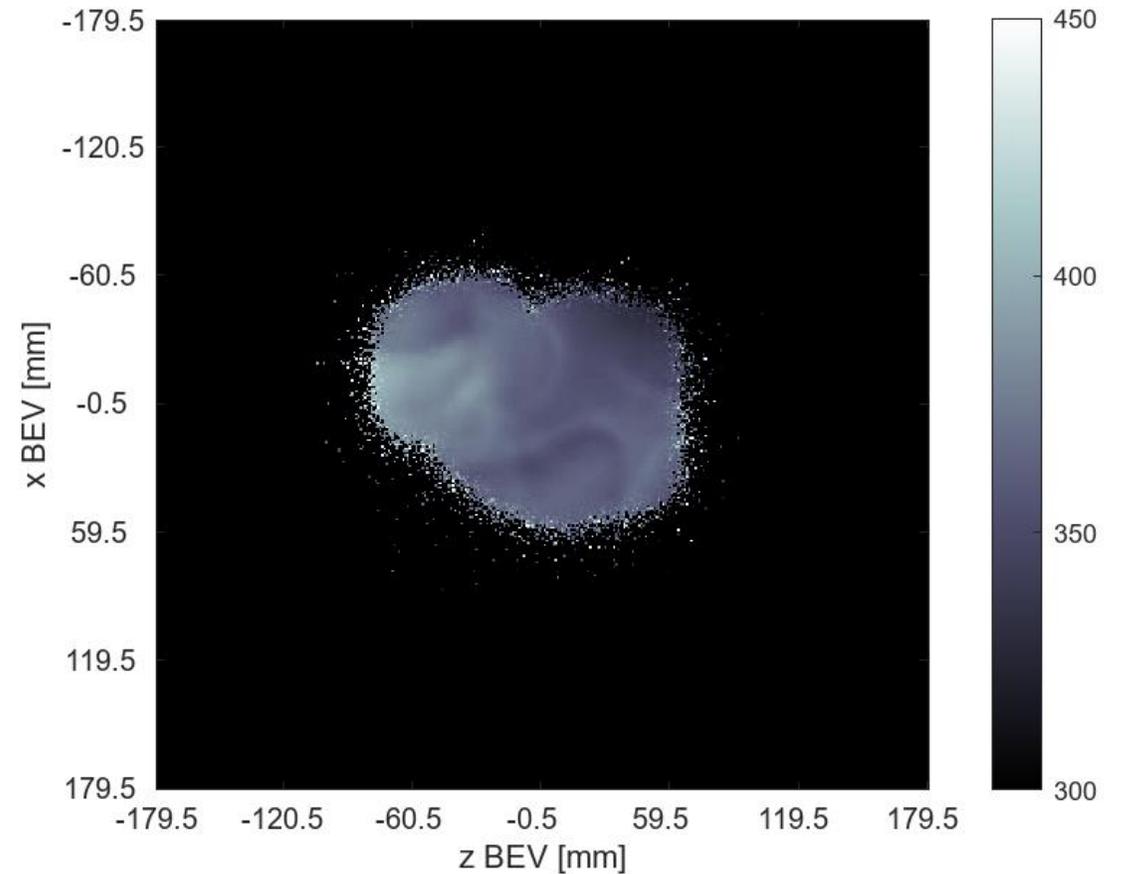
From initial/final energy calculate
WEPL = $R_{\text{Init}} - R_{\text{Final}}$



Reconstruct **particle path** and calculate intersection point with Isocenter plane



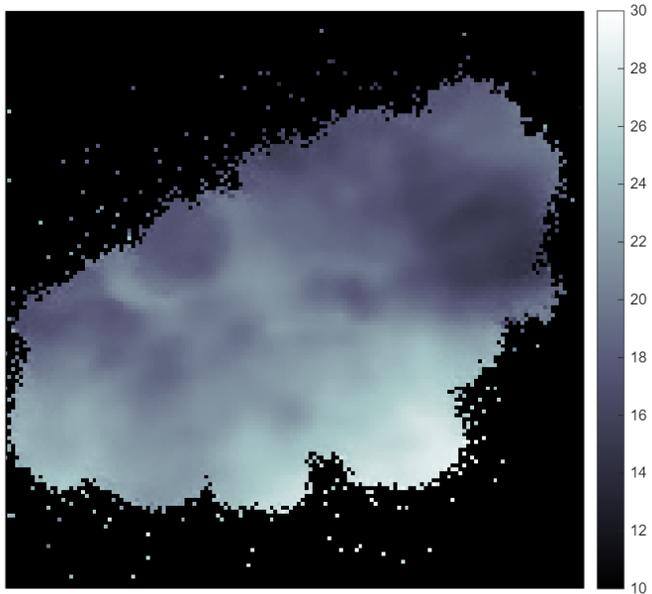
Calculate **mean WEPL** in each image pixel



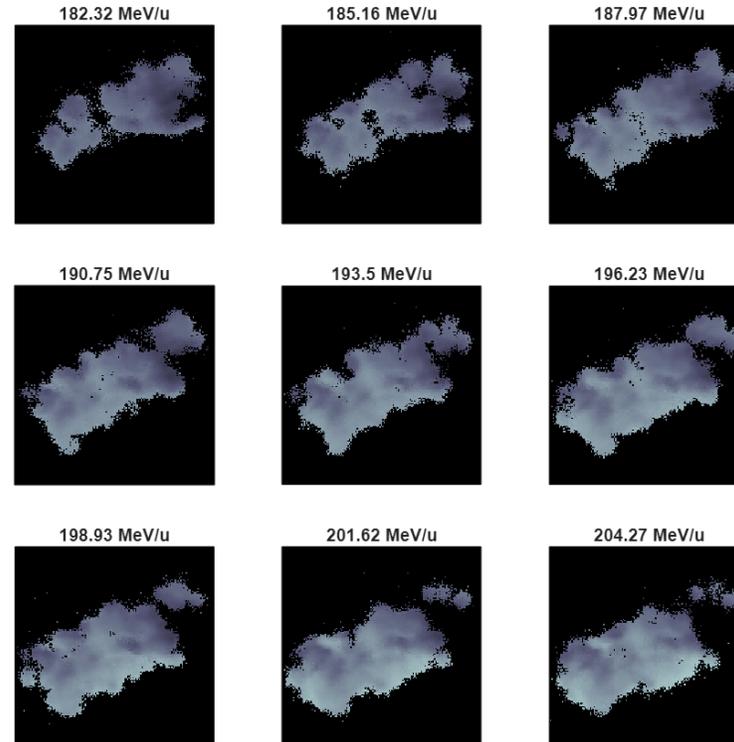
Reconstructed radiograph of prostate case

Simulation and reconstruction of radiographs III

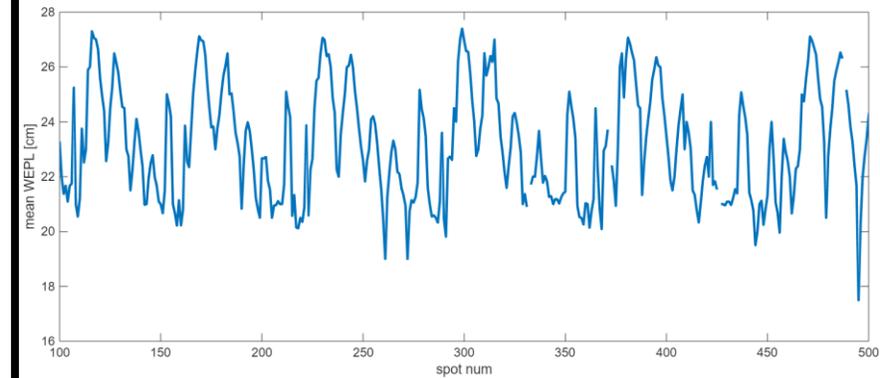
Full energy helium radiograph (FEHeRad)



Single energy helium radiograph (SEHeRad)



Spotwise WEPL



Hardt JJ et al. Phys Med Biol. 2024; 69(12)

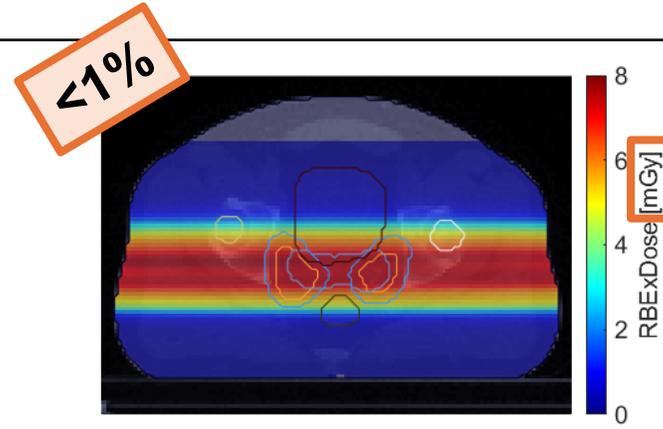
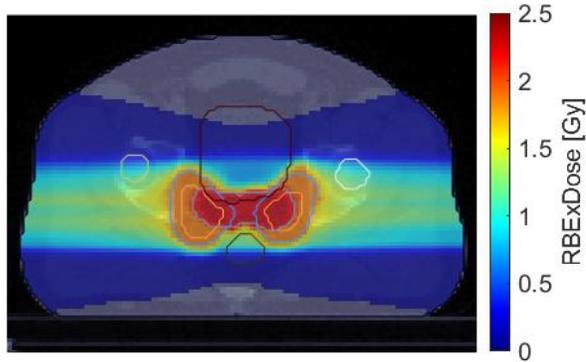
Treatment planning: carbon-helium beam dose

Prostate patient, optimized carbon RBExDose

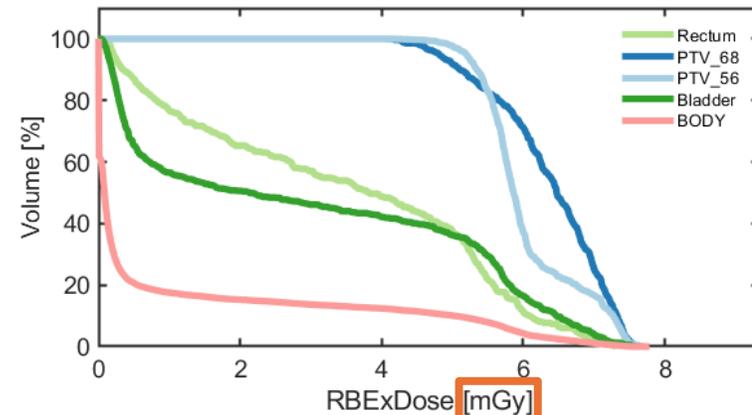
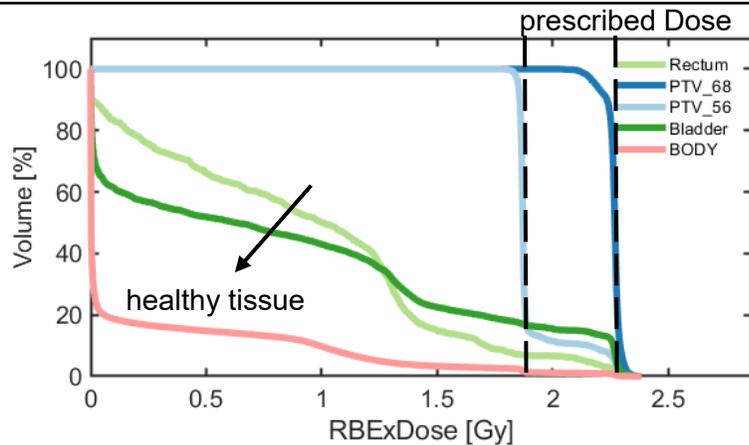
Carbon-Helium RBExDose

Helium RBExDose

Axial Dose Slice



Dose Volume Histogram



Hardt JJ et al. Phys Med Biol. 2024; 69(12)

matRad

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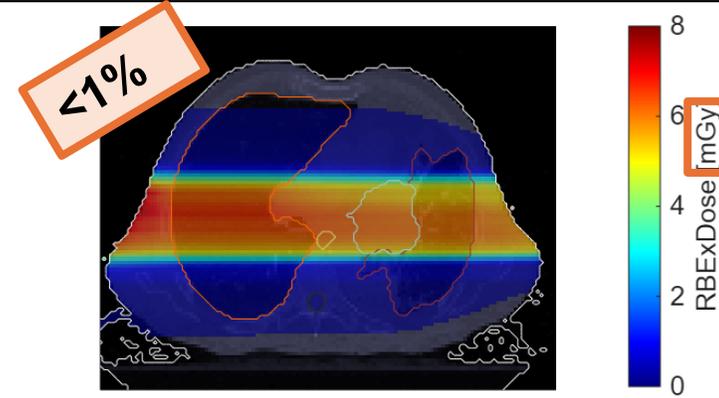
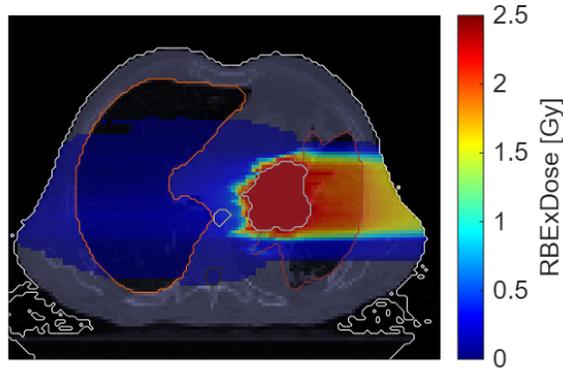
Treatment planning: lung case

Prostate patient, optimized carbon RBExDose

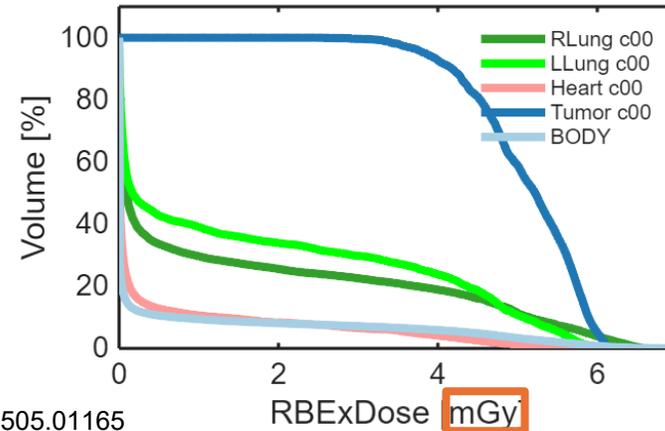
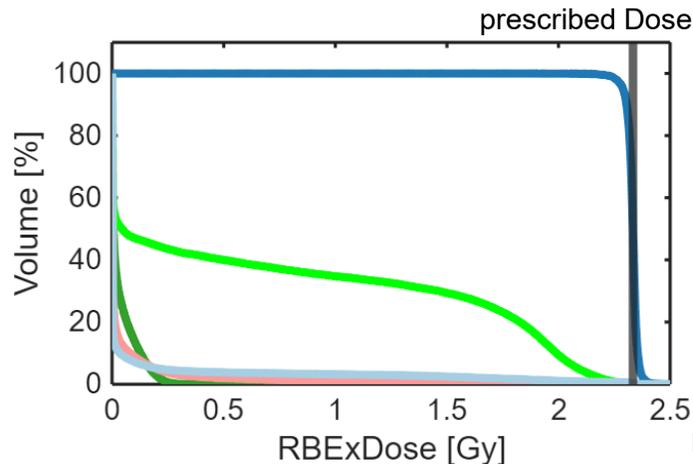
Carbon-Helium RBExDose

Helium RBExDose

Axial Dose Slice



Dose Volume Histogram



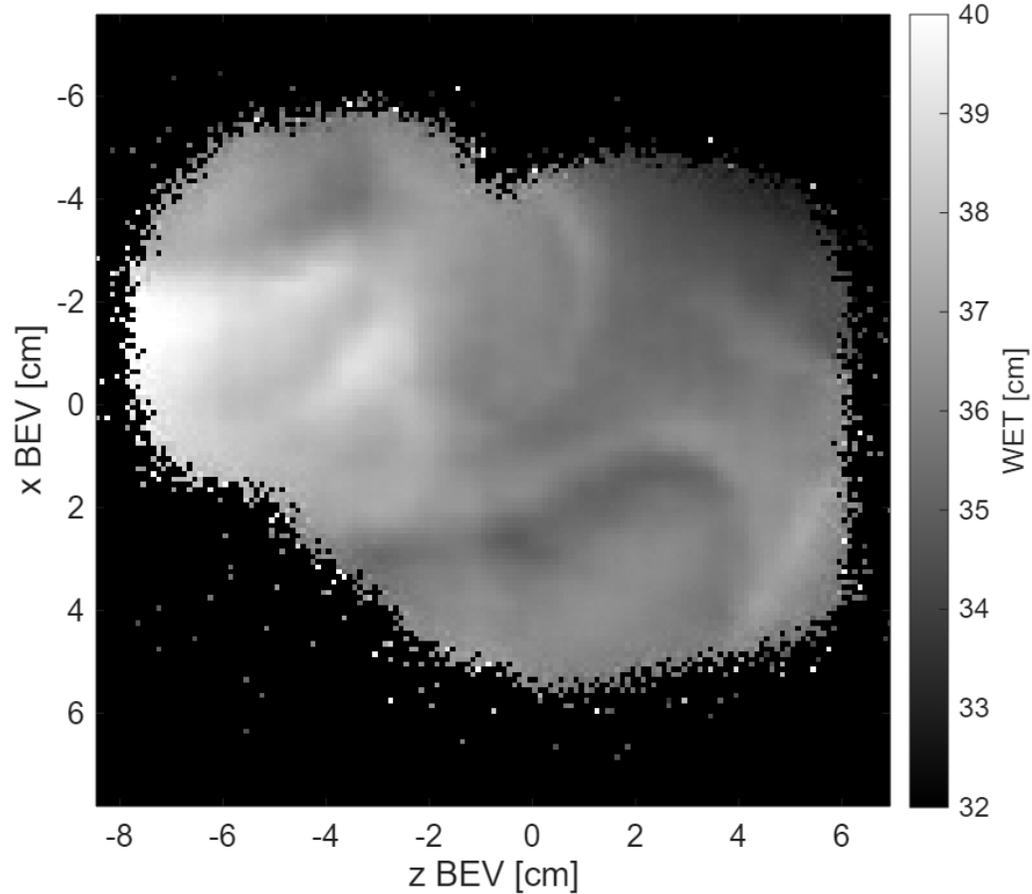
Hardt JJ et al. arXiv:2505.01165

matRad

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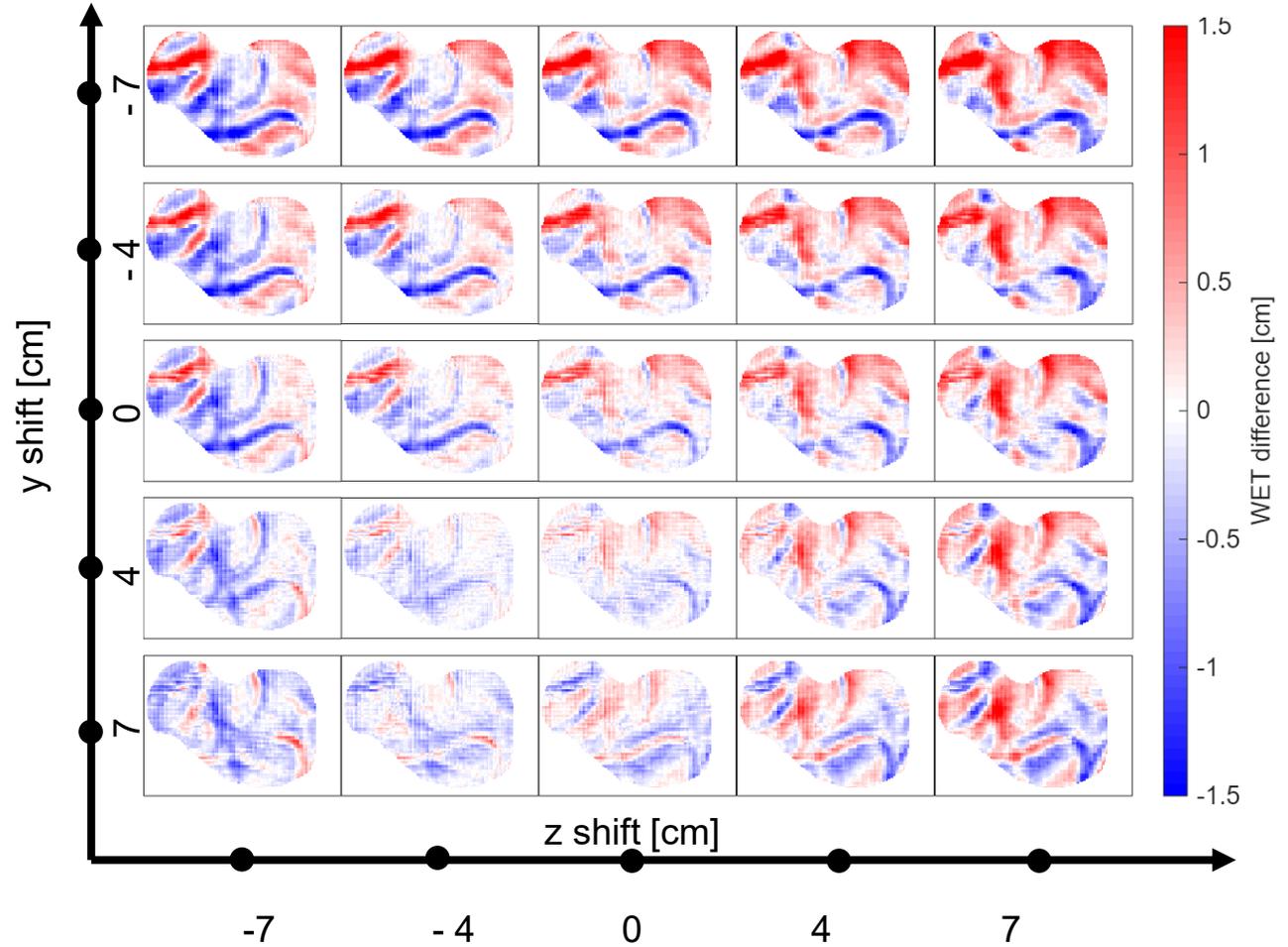
1 for a Life without Cancer

Application I: patient positioning



Helium radiograph, prostate case

Accuracy < 1mm



Difference to reference images

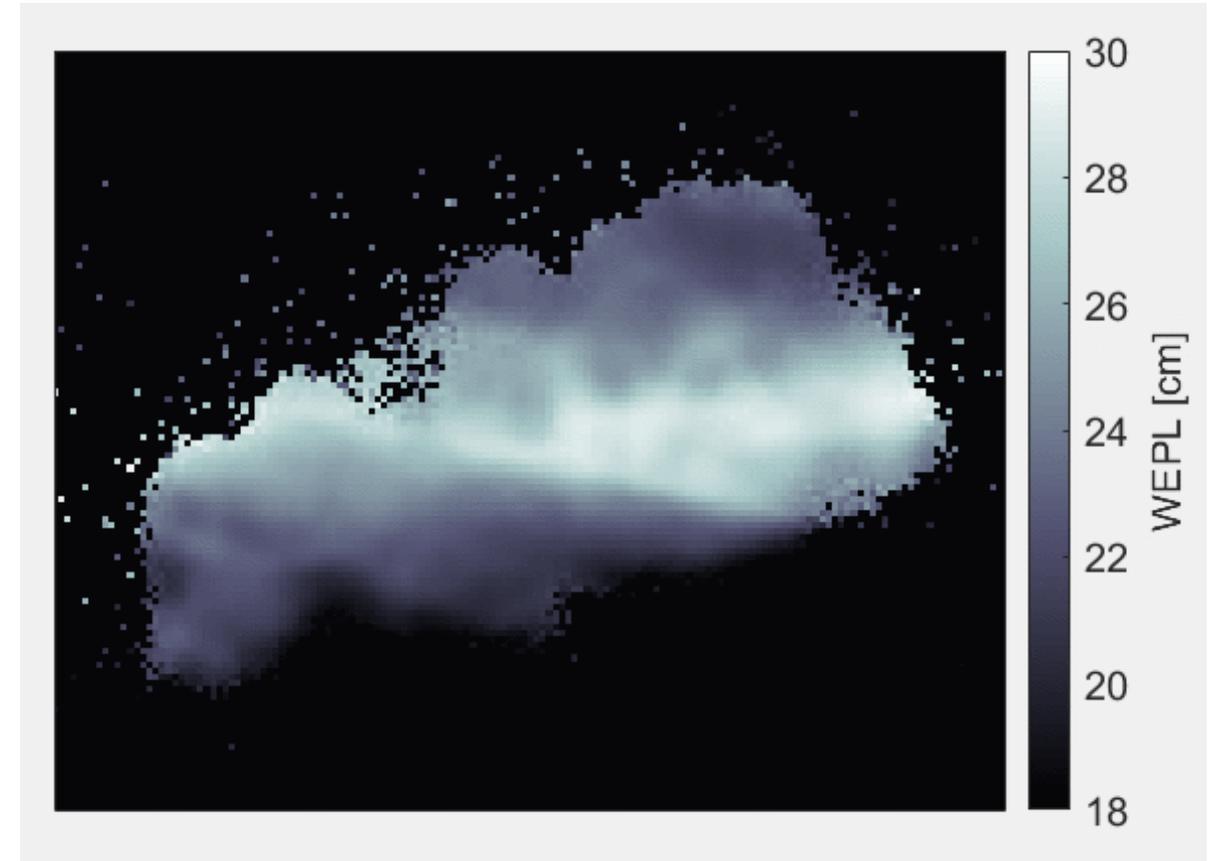
Hardt JJ et al. Phys Med Biol. 2024; 69(12)

Application II: intrafractional motion tracking

Relative motion between the tumor and the scanning beam causes deviations of the delivered dose distribution

Good to know motion/ breathing phase during irradiation

- minimum MSE
- Motion function: Segment spine and extract movement of COM of spine over time



Helium Radiograph (45, 223.56 MeV u), for all 10 phases

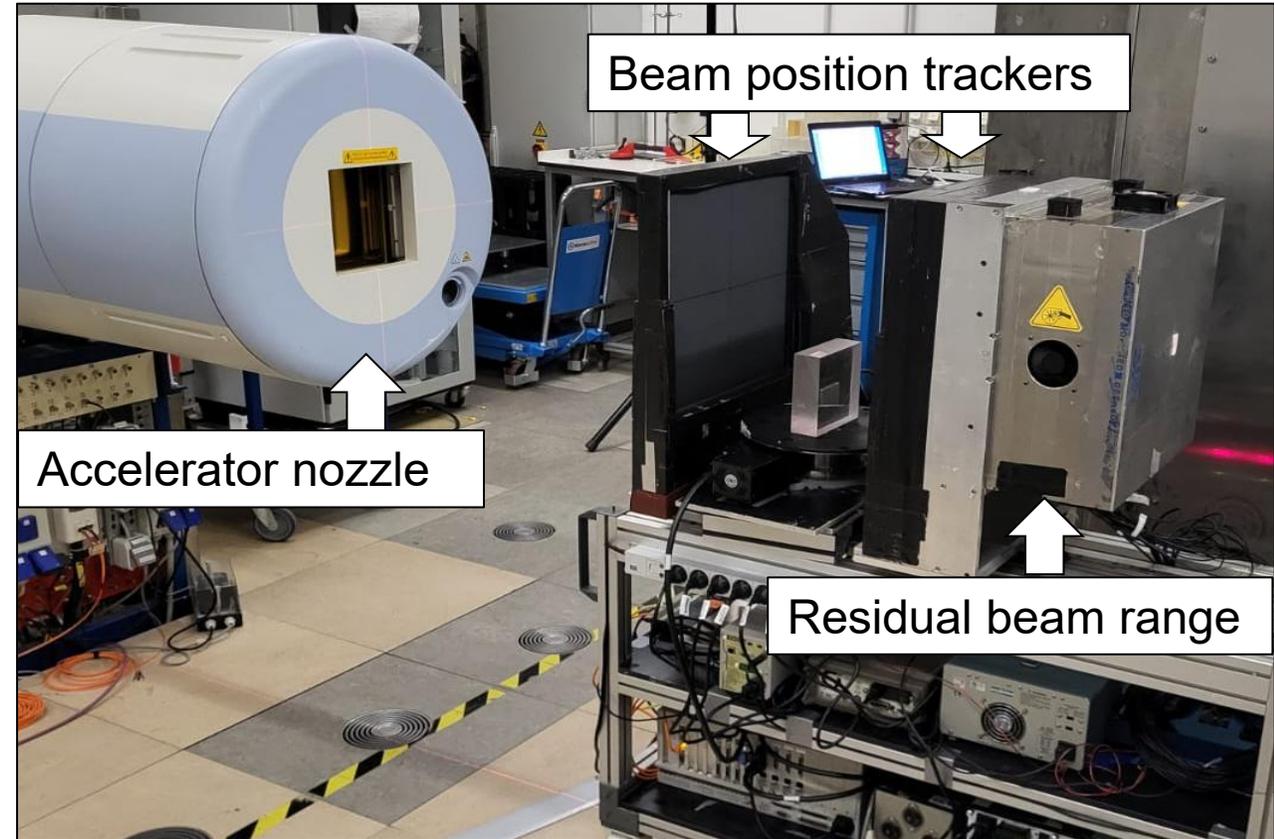
Experimental setup

HELIOS is based on the well-established technologies **HIT** multi-ion beam delivery (not in the same time) and **ProtonVDA** imaging detector (developed for specific proton beams).

Volz L et al. Phys Med Biol. 2020; 65(5):055002

DeJongh EA, et al. Med Phys. 2021; 48(3):1356-1364

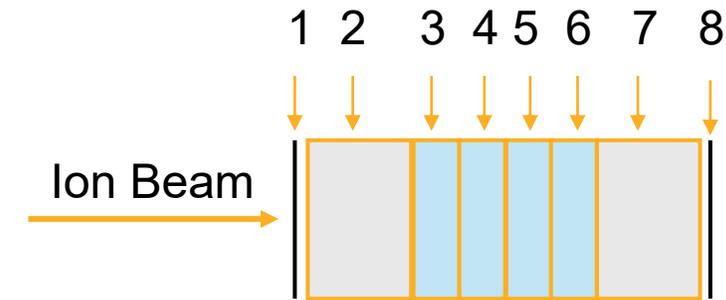
Event = Trigger (Energy detector) && ~~Upstream Tracker (4 hits)~~ && Downstream Tracker (4 hits)



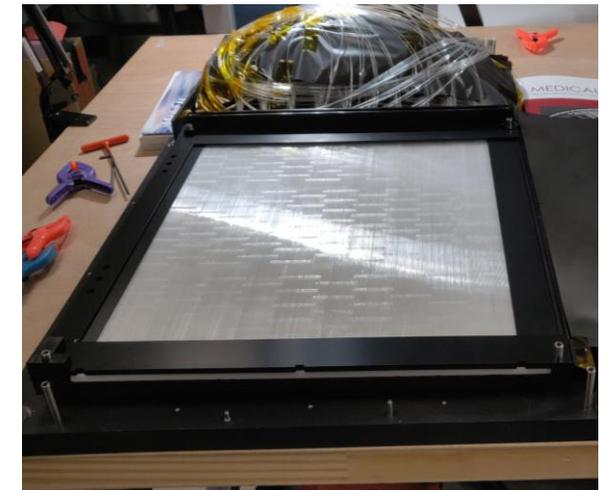
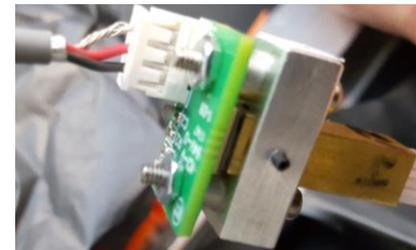
Ion imaging detector at the HIT experimental room

Imaging detector: position trackers

N, name	l (cm)	ρ (g/cm ³)
1, Black Kapton film	0.0075	1.42
2, Rohacell HF 031	0.6	0.032
3, Scint. fibers Y1	0.1	1.05
4, Scint. fibers Y2	0.1	1.05
5, Scint. fibers X1	0.1	1.05
6, Scint. fibers X2	0.1	1.05
7, Rohacell 31	0.6	0.032
8, Black Kapton film	0.0075	1.42



12 fibers per
1 SiPM
Spacing
32 mm



ProtonVDA

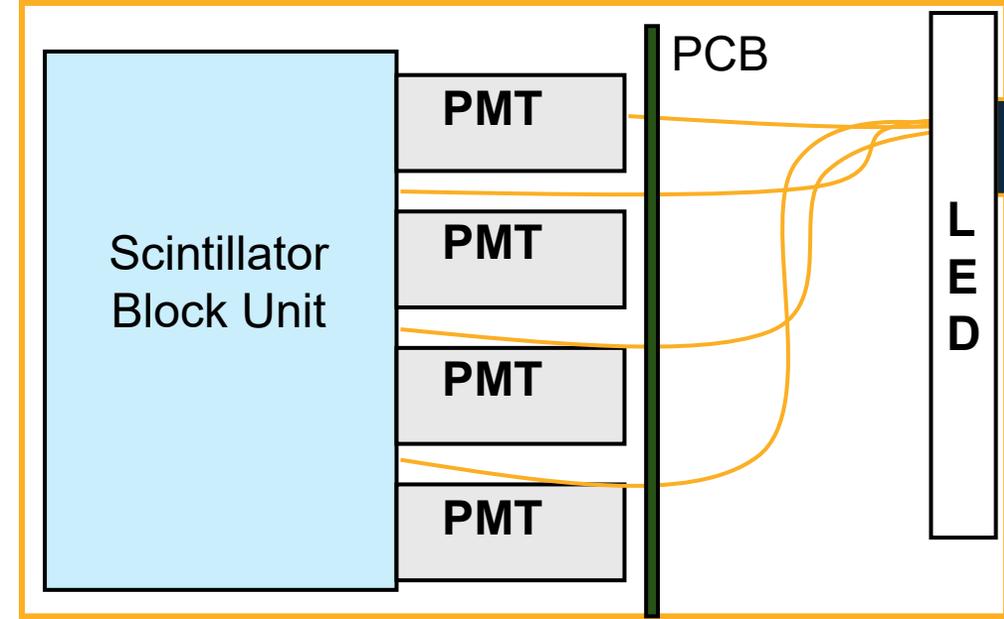
TRANSFORMING PROTON THERAPY

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Imaging detector: range detector

- PCB base to provide high voltage
- PMT to detect light
- Scintillator Block Unit, produces light when ions crosses the scintillating material
- 3 ADC channels:
 - E, the sum of the sixteen PMT signals
 - U, Diagonal sum with different weights
 - V, Diagonal sum with different weights



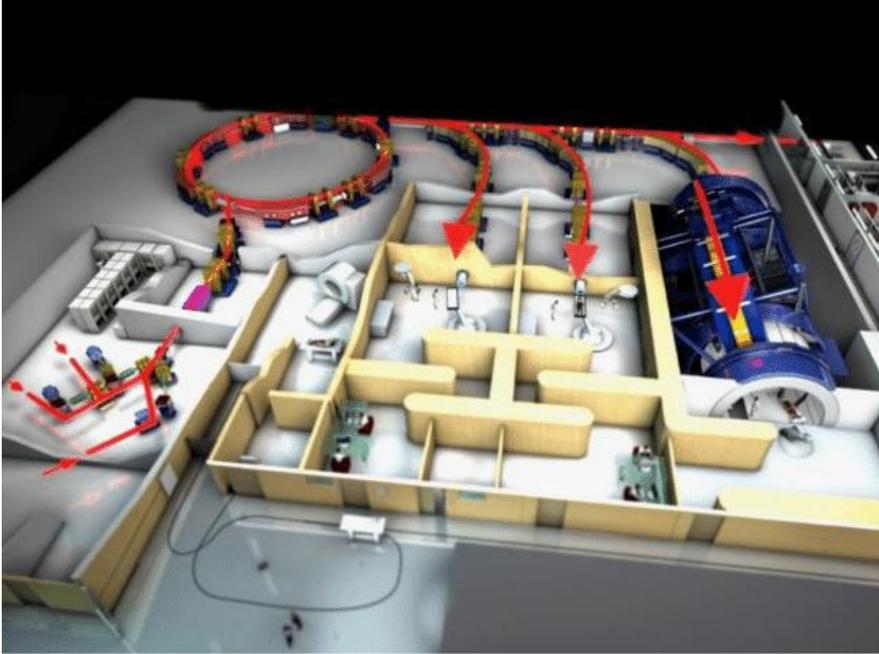
E

U

V

+1	+1	+1	+1		+1	+2	+3	-3	-2	-1	
+1	+1	+1	+1	-1		+1	+2	-2	-1		+1
+1	+1	+1	+1	-2	-1		+1	-1		+1	+2
+1	+1	+1	+1	-3	-2	-1			+1	+2	+3

Beam source – HIT synchrotron

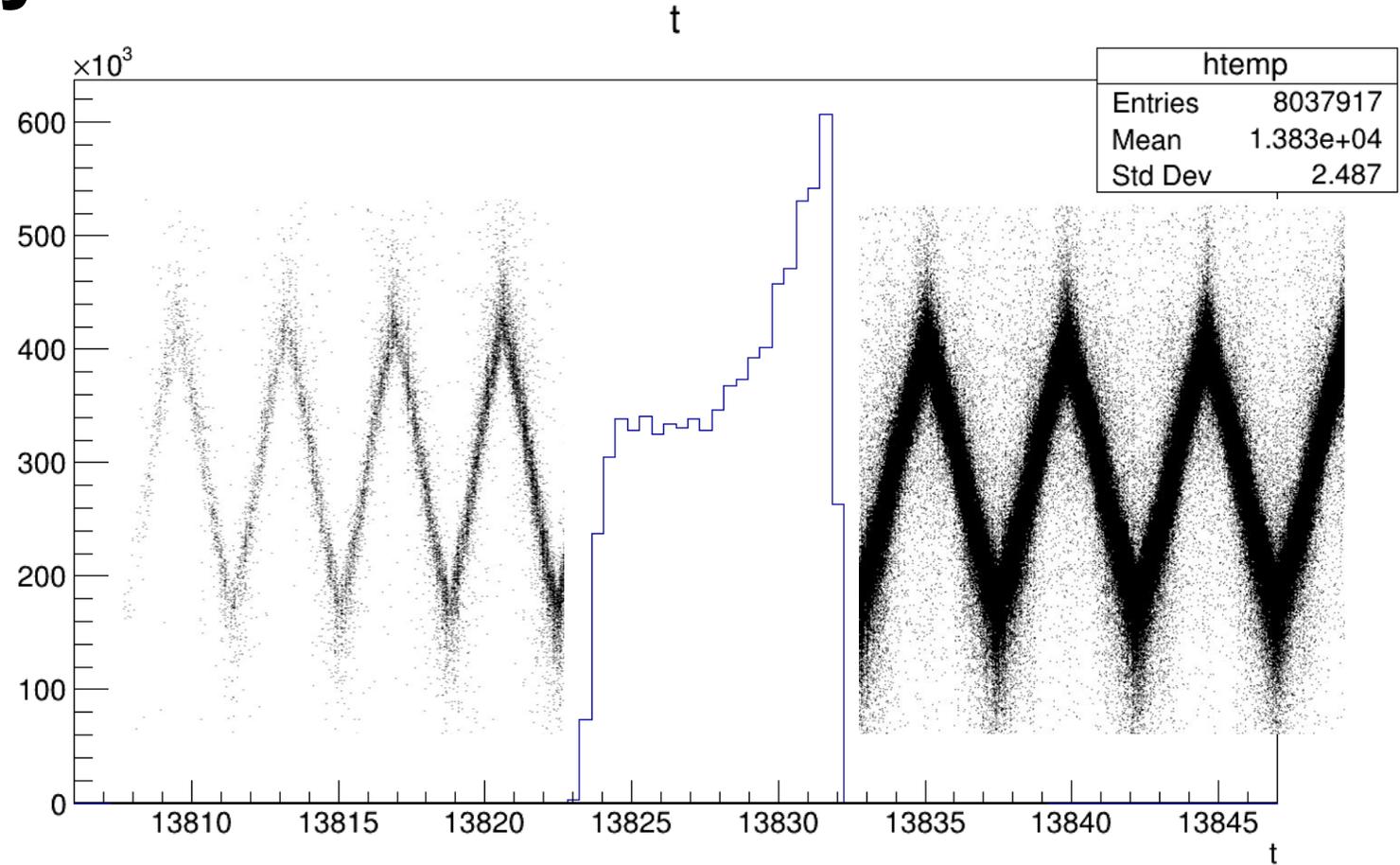


Ions used: p, He

Beam energy: 50 - 220 MeV/u

Beam intensities: ~3 MHz(p), ~1 MHz(He)

Pulsed mode: T = 8 sec; Continuous scanning



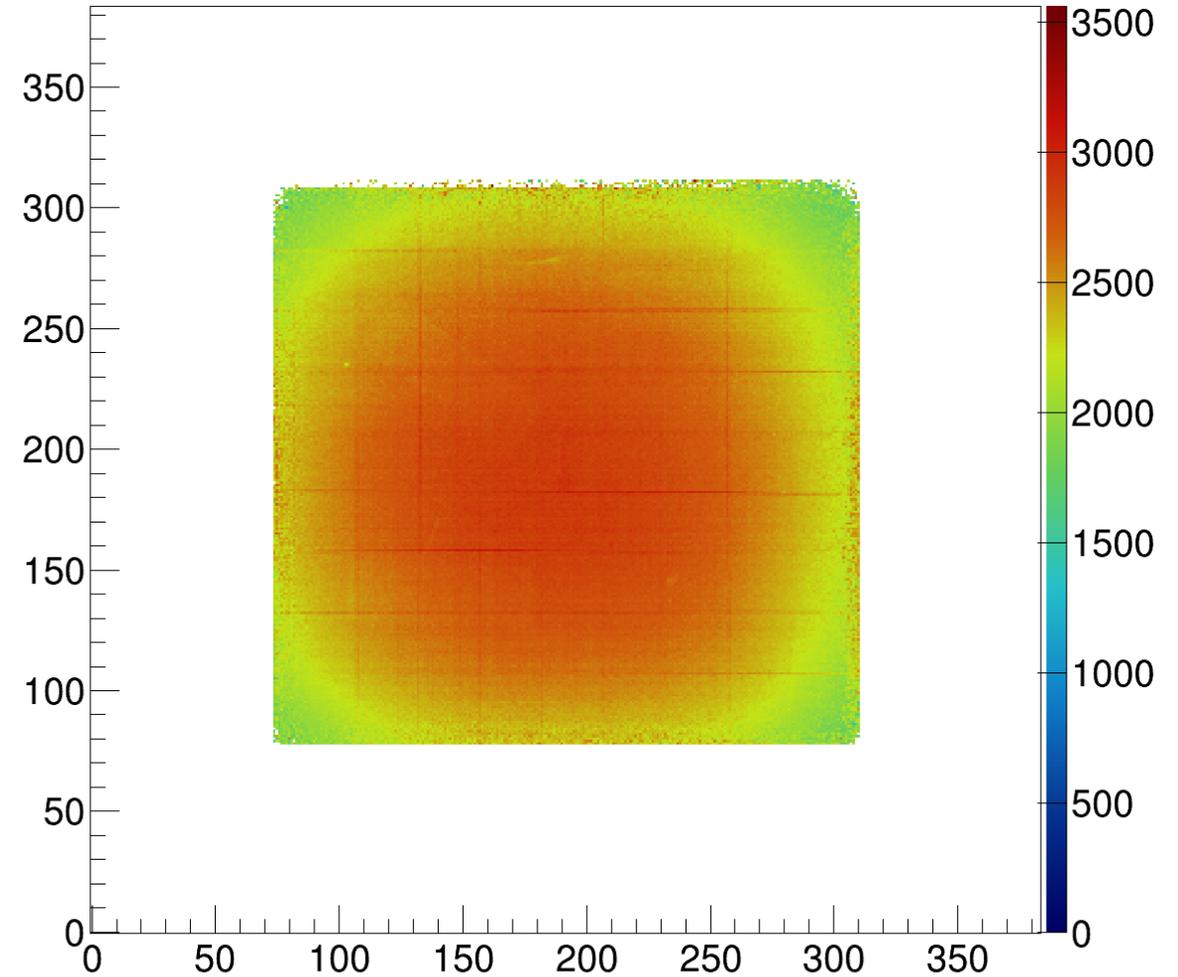
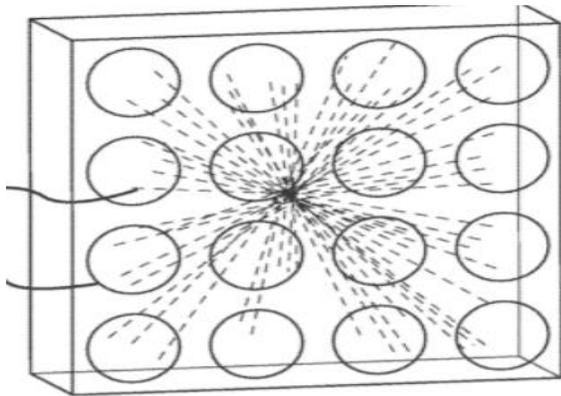
Range detector calibration

Calibration of the energy detector to obtain covariance matrix for each spot (X, Y, Residual Range):

$$K_{EUV} = \begin{bmatrix} cov(EE) & cov(EU) & cov(VE) \\ cov(UE) & cov(UU) & cov(UV) \\ cov(VE) & cov(VU) & cov(VV) \end{bmatrix}$$

50 different energies ~ 50 – 120 MeV

Low energy cut to filter our fragments

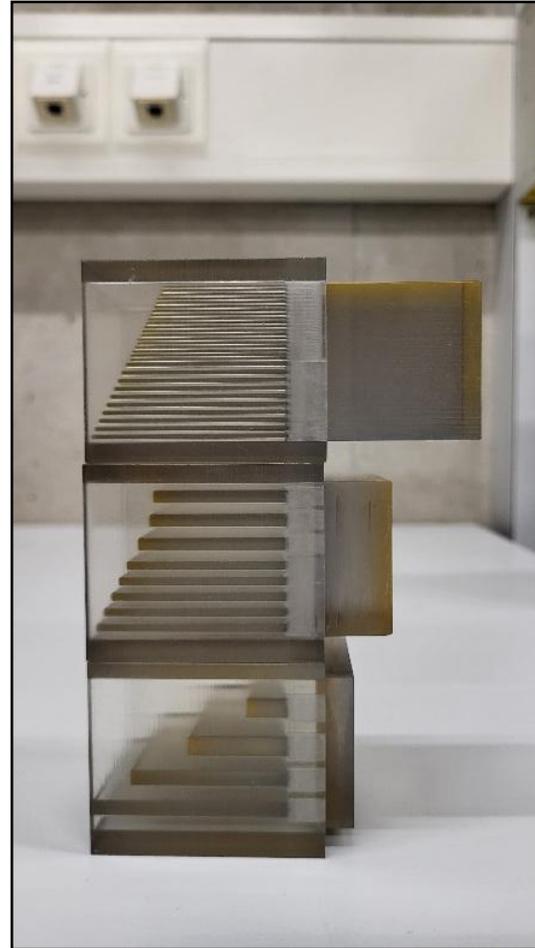
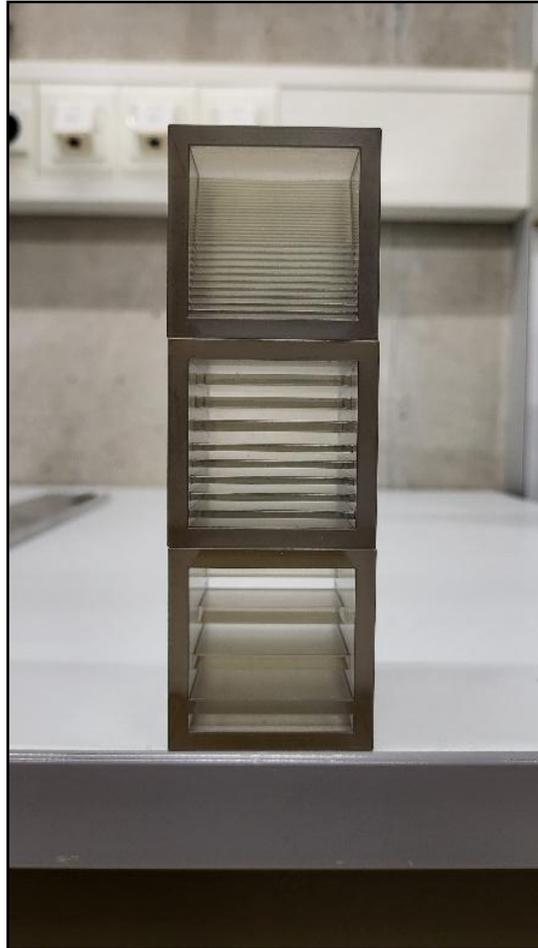


3D printed phantoms

Material:
VeroClear-RGD810

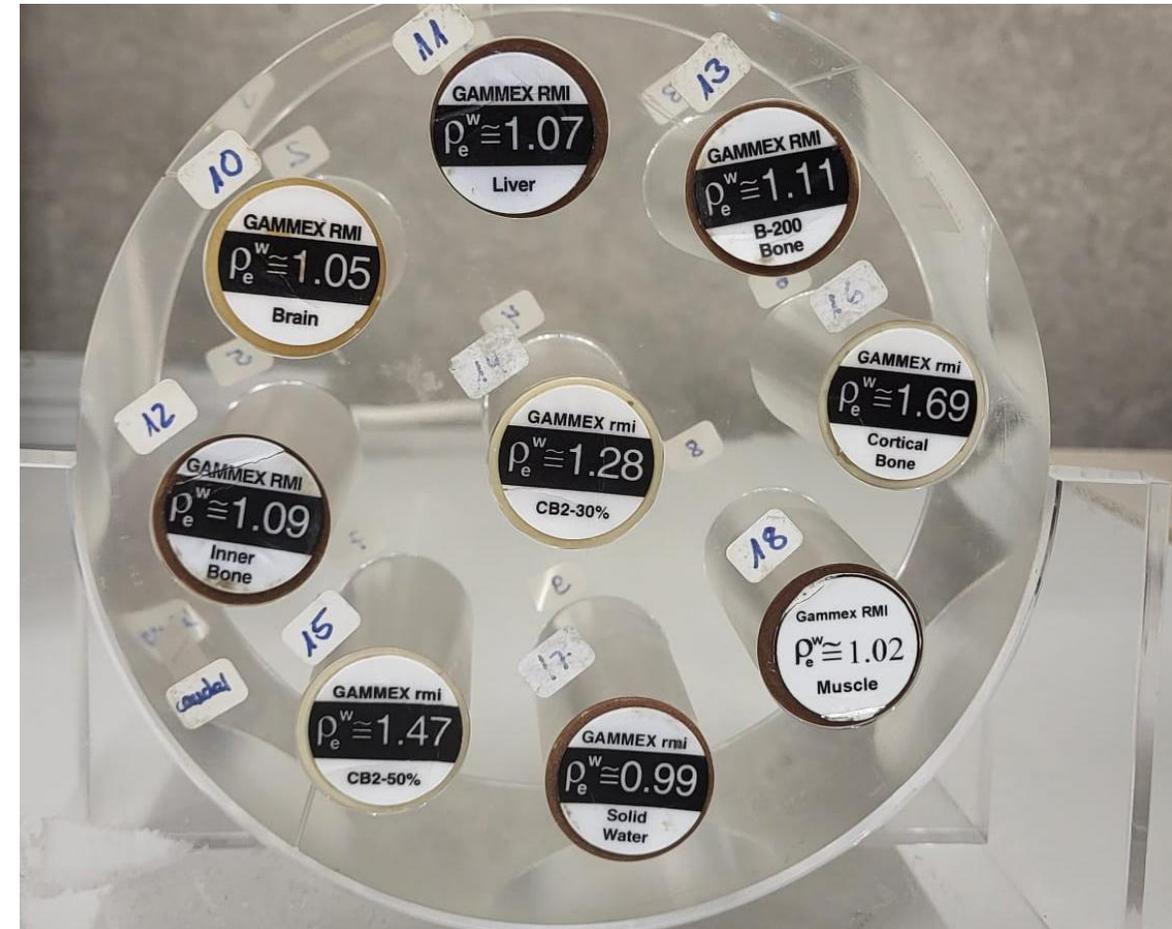
$$\rho = 1.19 \text{ g/cm}^3$$

Spacing and depth
of lines or holes
from 5 mm to 0.5
mm



Gammex 467 tissue inserts

N	Material	$\rho \times \text{length [cm]}$
	PMMA	11.57 ± 0.02
14	CB2-30%	8.95 ± 0.07
11	Liver	7.43 ± 0.04
10	Brain	7.33 ± 0.04
12	Inner Bone	7.57 ± 0.05
15	CB2-50%	10.36 ± 0.06
17	Solid Water	6.90 ± 0.04
18	Muscle	7.15 ± 0.01
13	B-200 Bone	7.69 ± 0.05

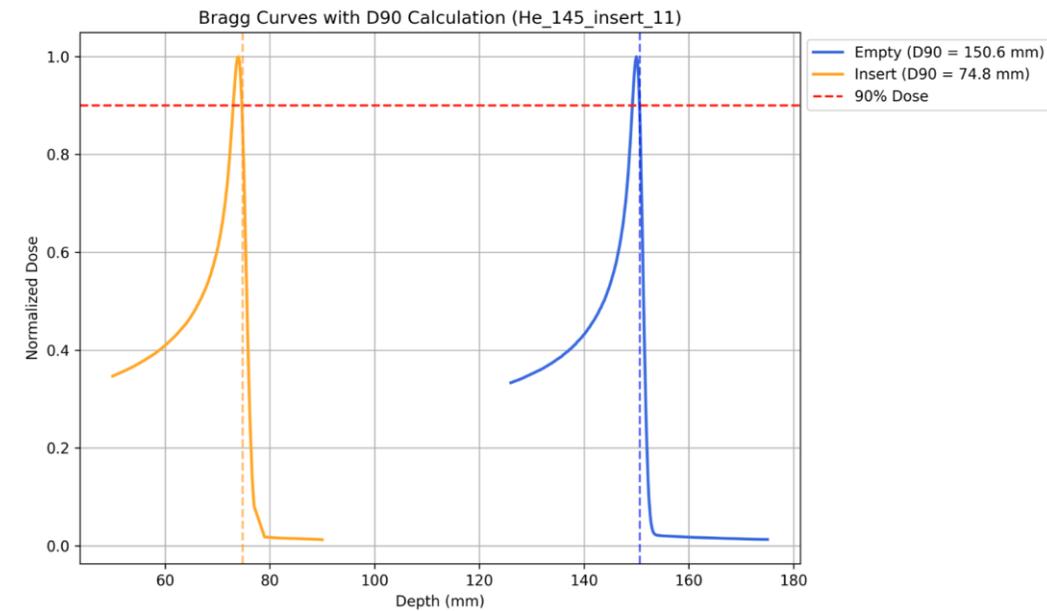


Gammex 467 WET check

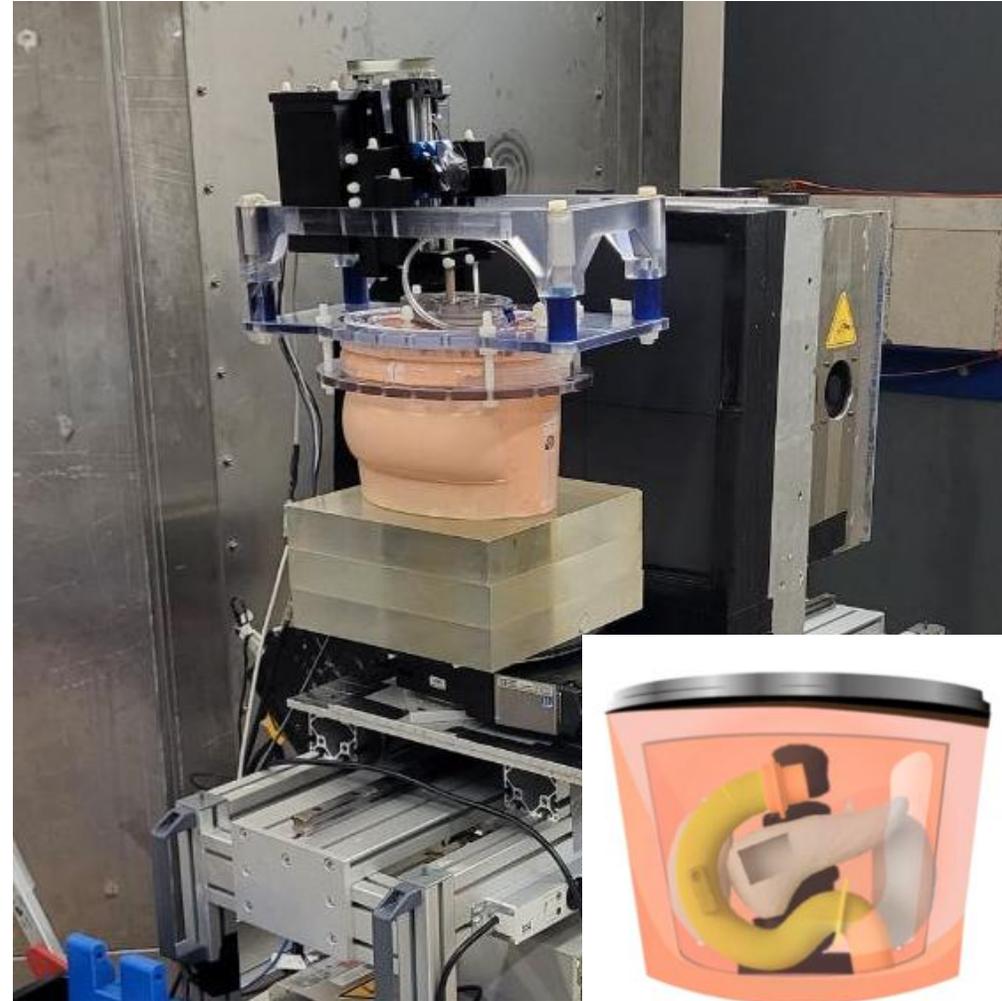


PTW PeakFinder TM

Sánchez-Parcerisa D Phys Med Biol.
2012; 57(11):3629-41.



Anthropomorphic phantoms



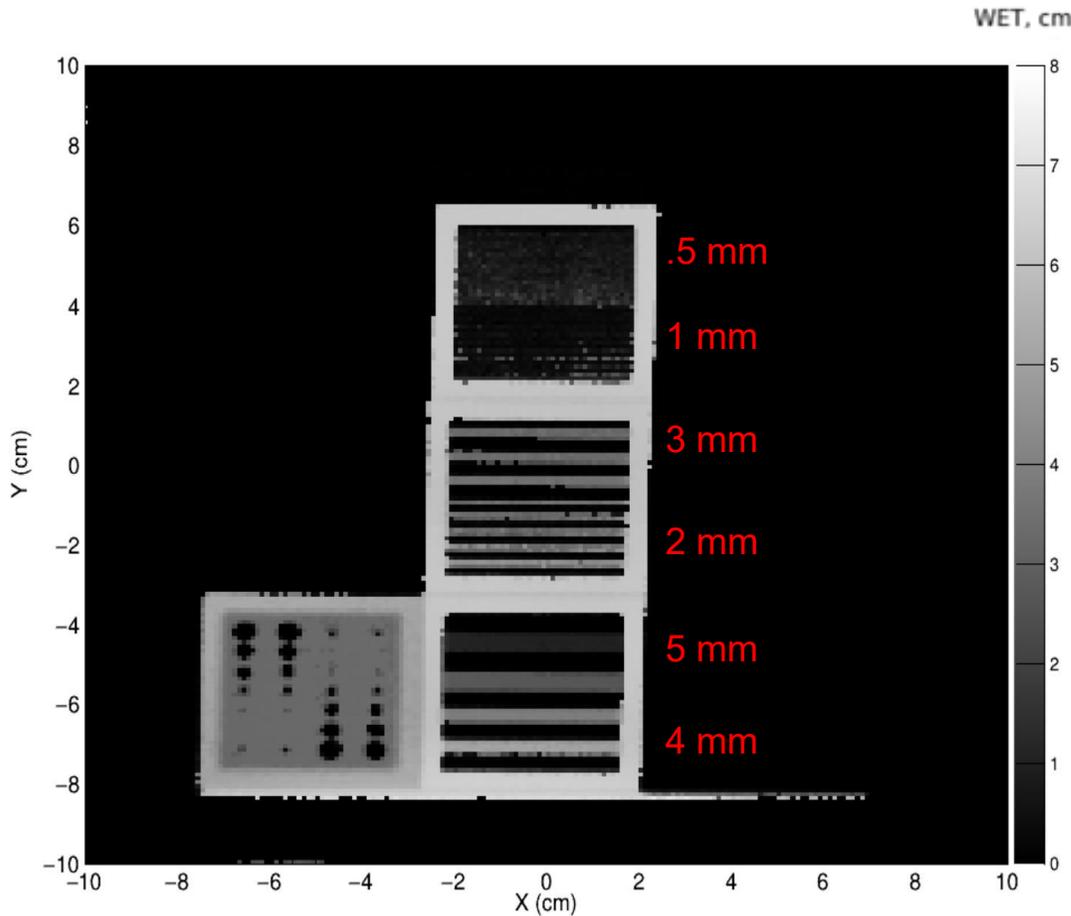
Two phantom with dynamic capacities:

Bakhtiari Moghaddam A et al. PO-2314 ESTRO-2023

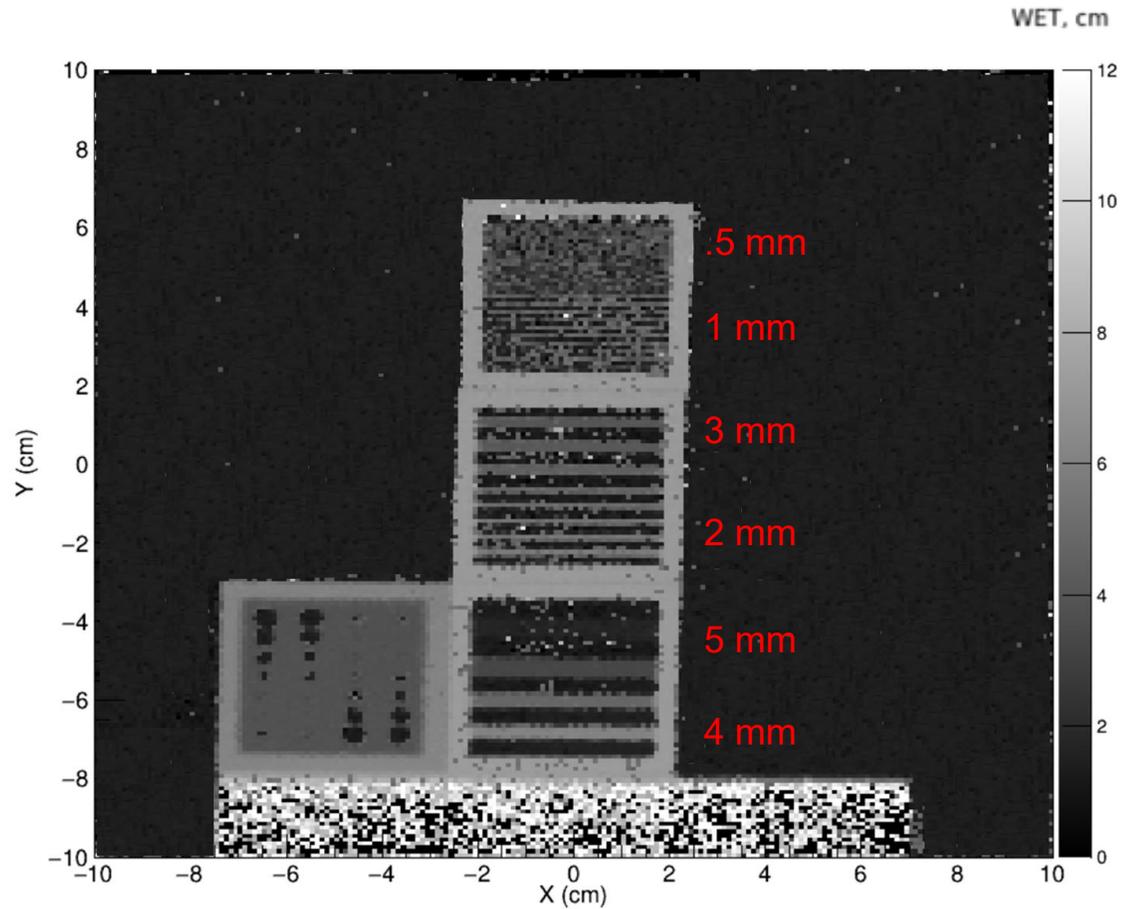
Stengl C et al. Phys Med Biol. 2023 11;68(24).



Spatial resolution measurements

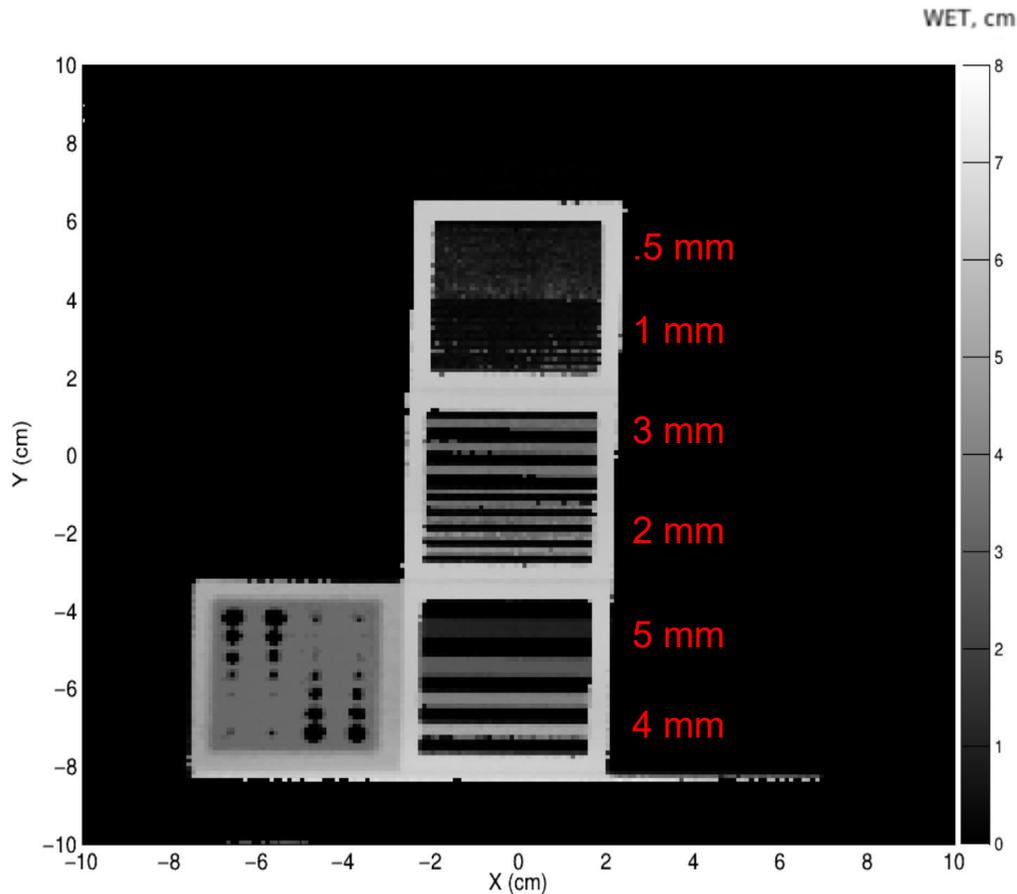


pRad (100, 125, 145 MeV)

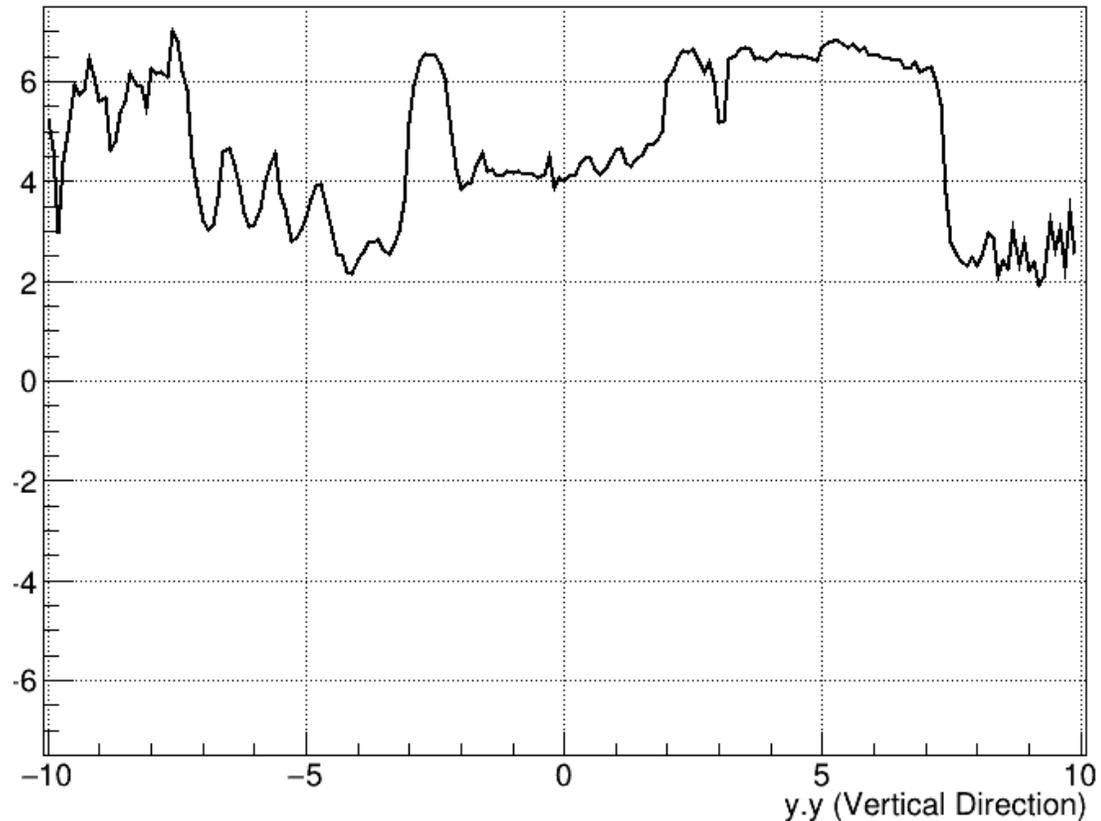


HeRad (100, 125, 145 MeV/u)

Spatial resolution measurements

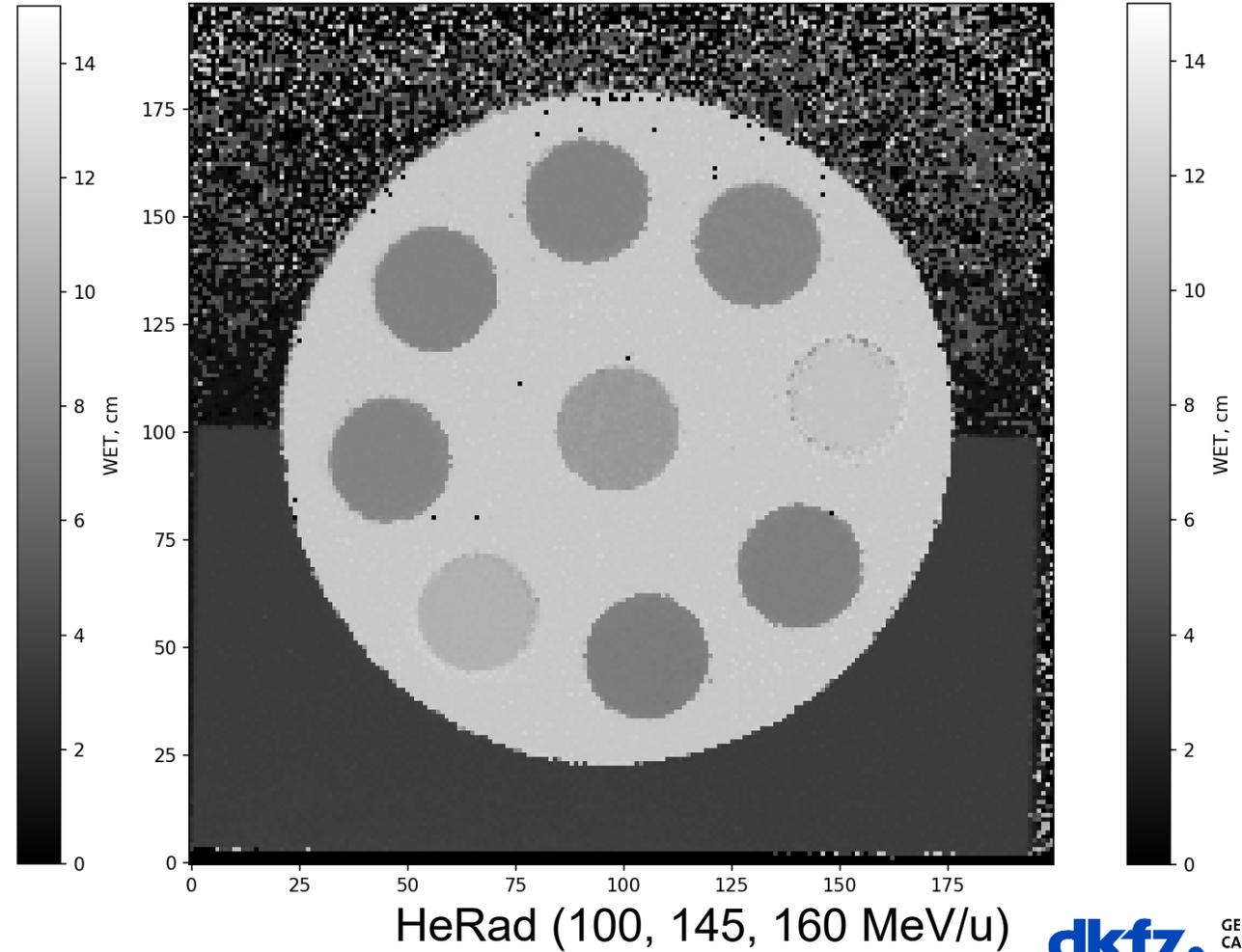
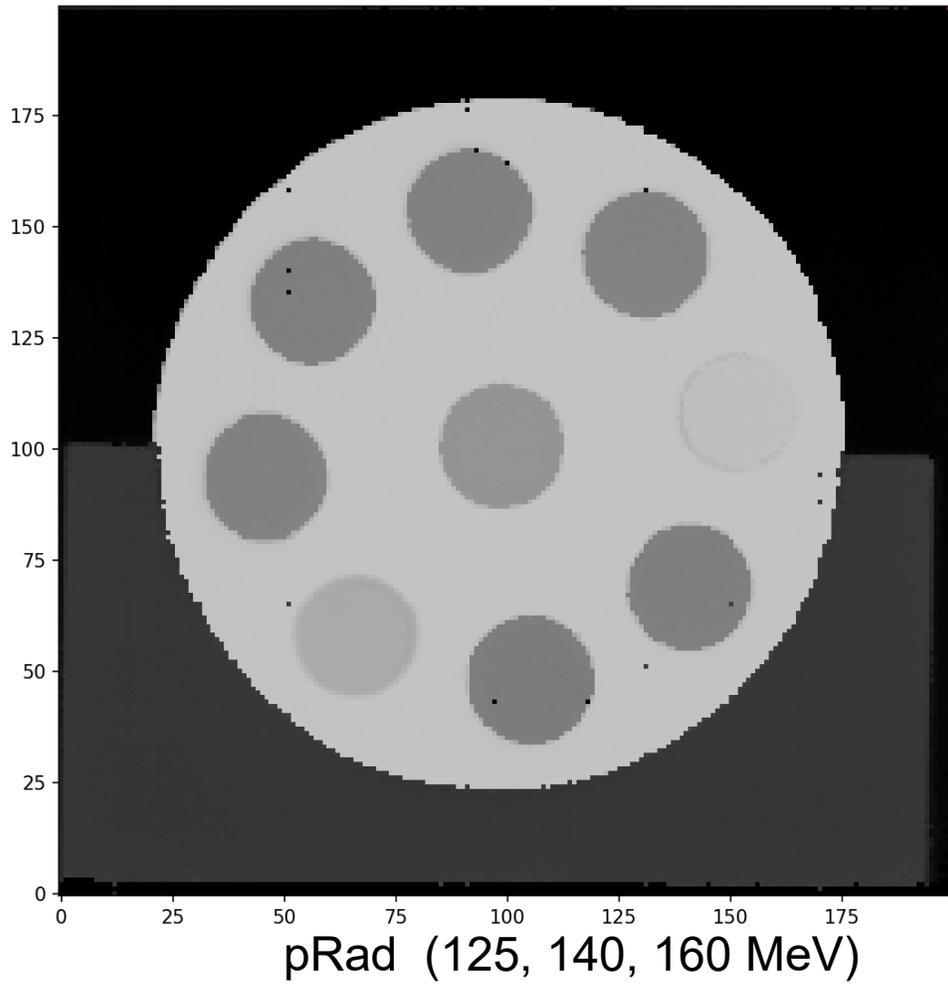


pRad (100, 125, 145 MeV)



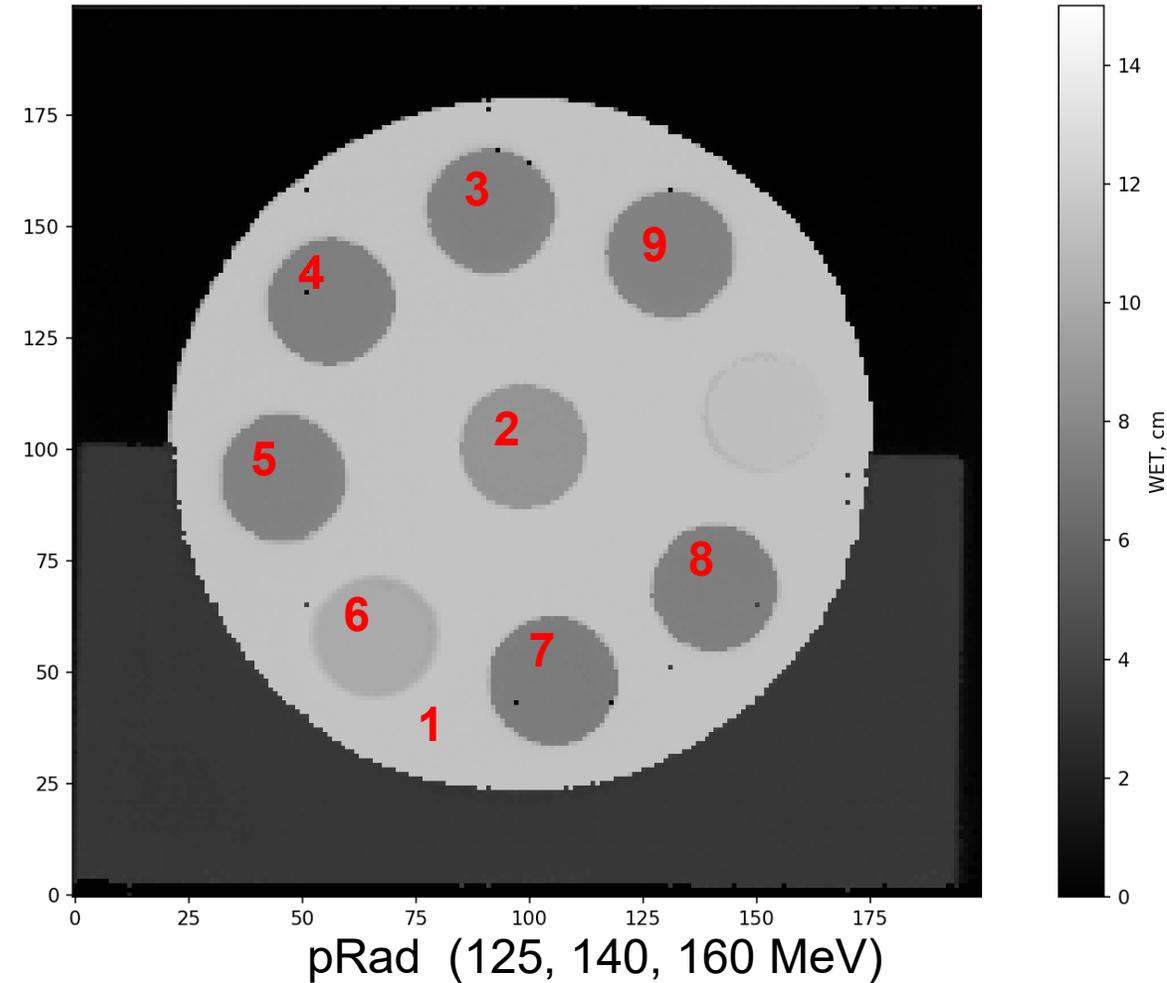
Single energy analysis

Gammex 467 Tissue Inserts



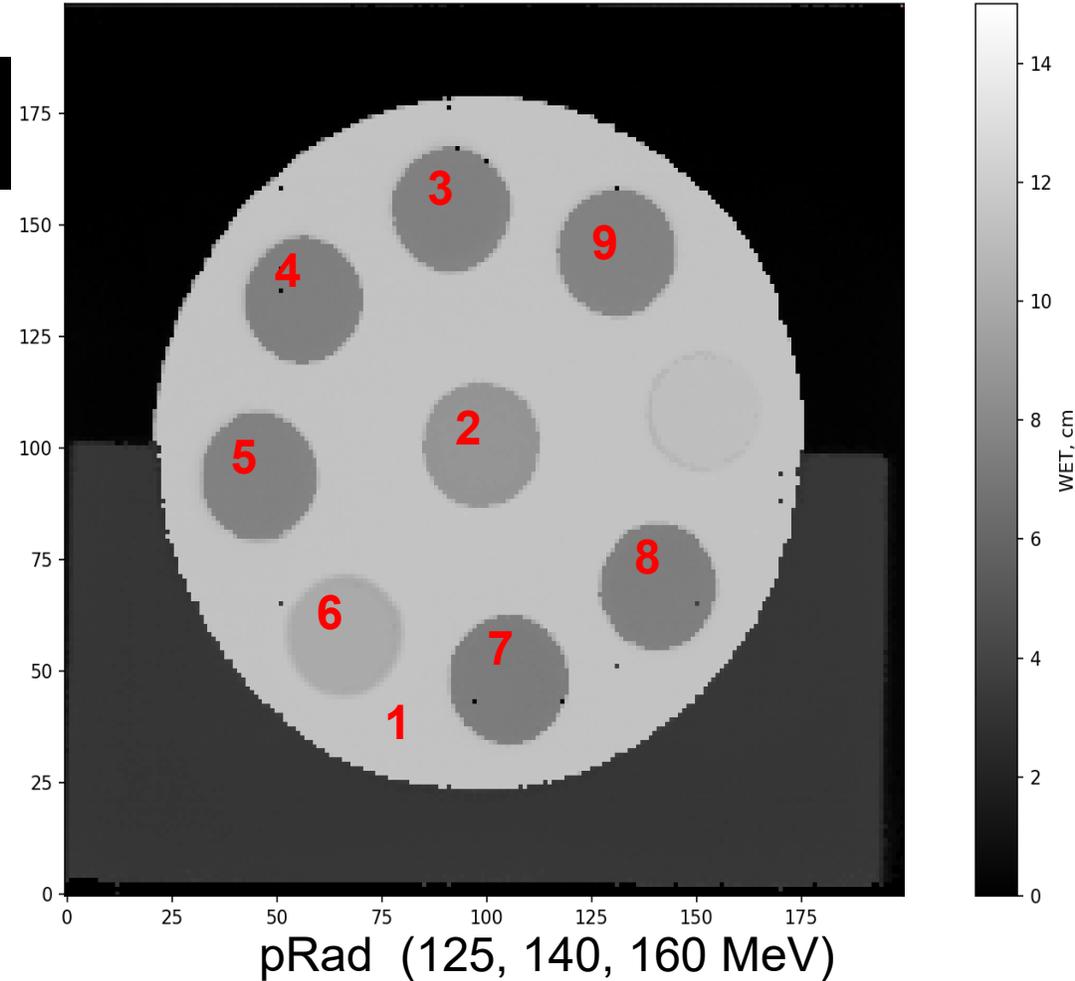
Gammex 467 Tissue Inserts

N	Material	GT WET [cm]	pRad WET [cm]	HeRad [cm]
1	PMMA	11.57±0.02	11.49±0.02	11.76±0.14
2	CB2-30%	8.95±0.07	8.97±0.03	8.96±0.13
3	Liver	7.43±0.04	7.45±0.02	7.68±0.06
4	Brain	7.33±0.04	7.38±0.02	7.56±0.05
5	Inner Bone	7.57±0.05	7.46±0.02	7.65±0.06
6	CB2-50%	10.36±0.06	10.03±0.03	10.40±0.06
7	Solid Water	6.90±0.04	6.96±0.02	7.20±0.05
8	Muscle	7.15±0.01	7.19±0.02	7.39±0.06
9	B-200 Bone	7.69±0.05	7.56±0.02	7.80±0.06



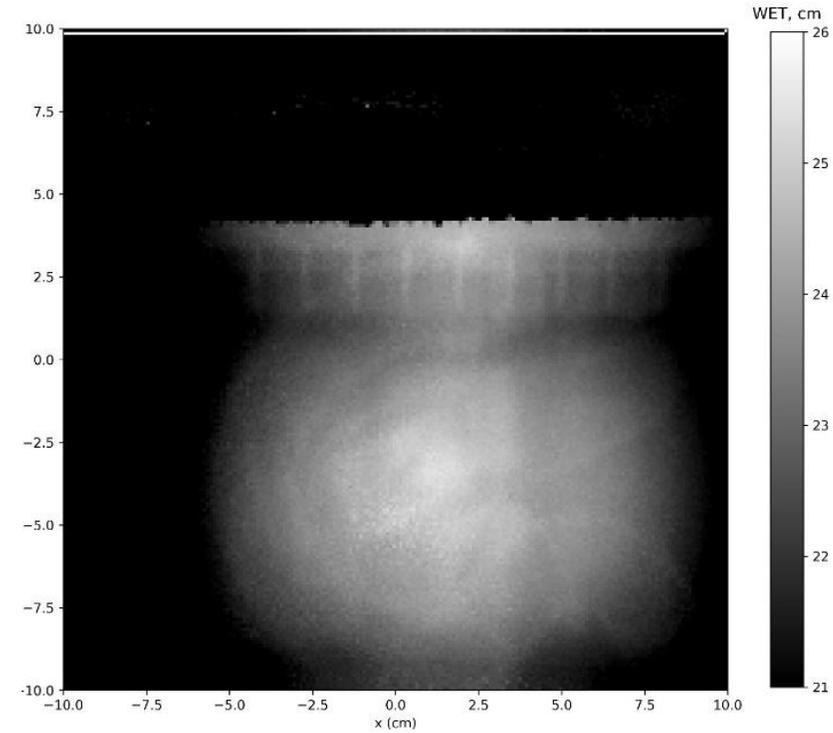
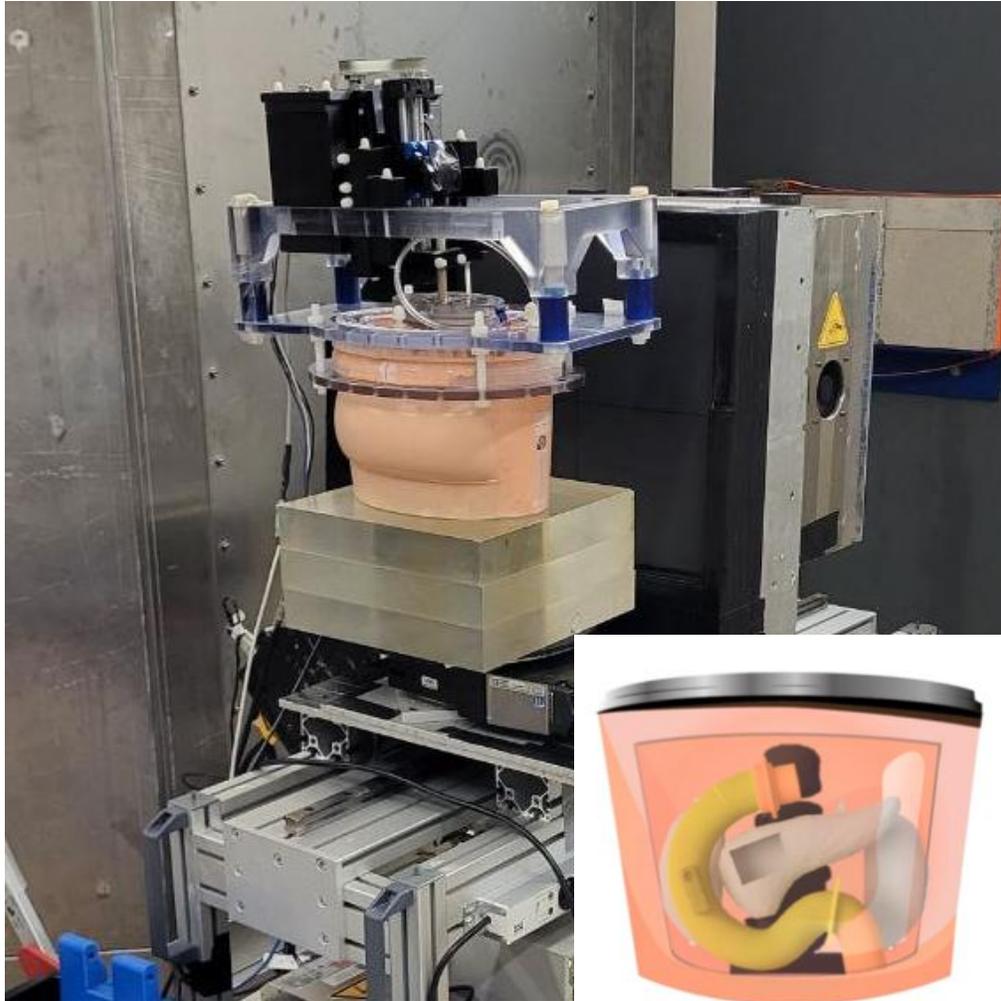
Gammex 467 Tissue Inserts

N	Material	pPF [cm]	WET [cm]	pRad [cm]	WET HePF [cm]	WETHeRad [cm]
1	PMMA	11.57±0.04	11.49±0.02	11.59±0.04	11.76±0.14	
2	CB2-30%	8.88±0.04	8.97±0.03	8.90±0.04	8.96±0.13	
3	Liver	7.58±0.04	7.45±0.02	7.60±0.04	7.68±0.06	
4	Brain	7.50±0.04	7.38±0.02	7.52±0.04	7.56±0.05	
5	Inner Bone	7.60±0.04	7.46±0.02	7.60±0.04	7.65±0.06	
6	CB2-50%	10.10±0.04	10.03±0.03	10.12±0.04	10.40±0.06	
7	Solid Water	7.04±0.04	6.96±0.02	7.08±0.04	7.20±0.05	
8	Muscle	7.26±0.04	7.19±0.02	7.30±0.04	7.39±0.06	
9	B-200 Bone	7.70±0.04	7.56±0.02	7.72±0.04	7.80±0.06	



Measurements are presented at 160 MeV/u for both protons and helium ions.

Abdominal phantom



pRad (210 MeV)

Overview of related projects

1. Speed up the DAQ system for the range detector



2. Fragments filtration for helium radiography and computed tomography



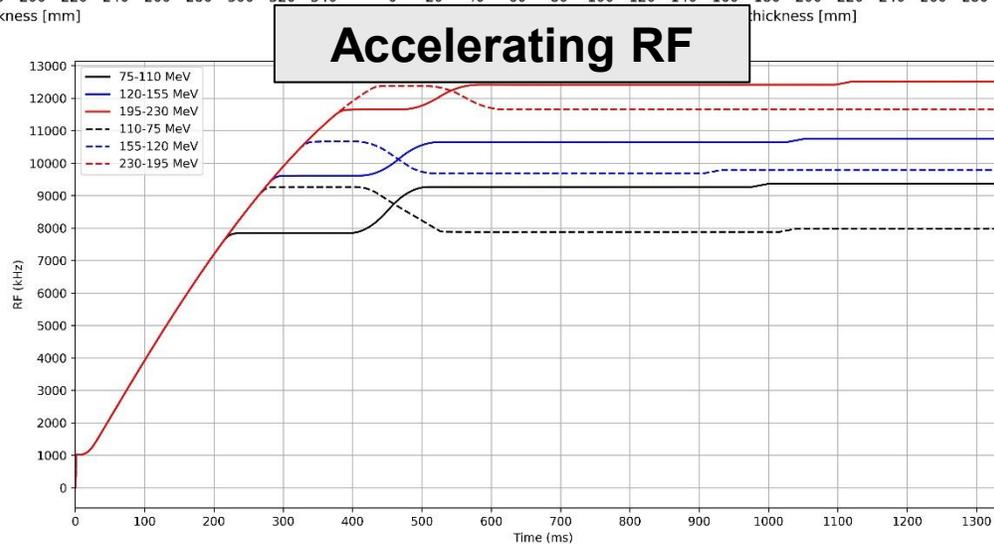
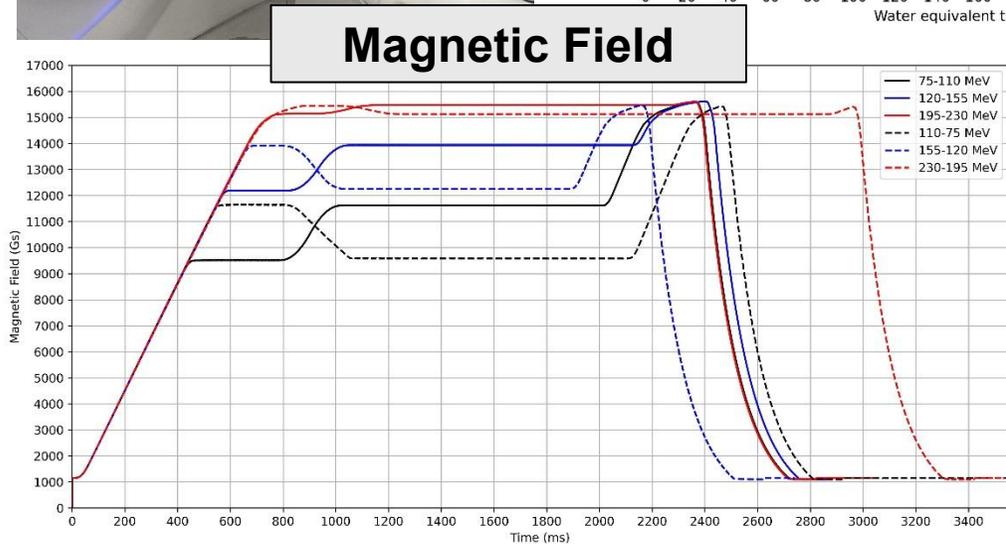
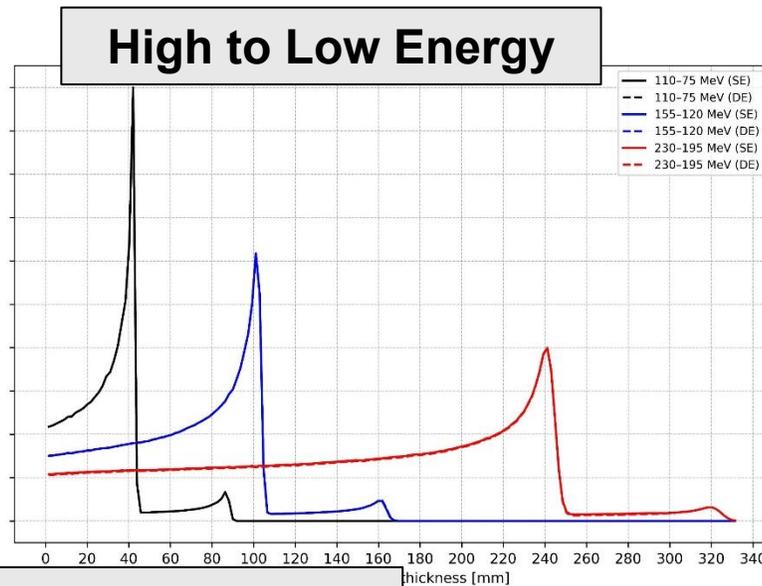
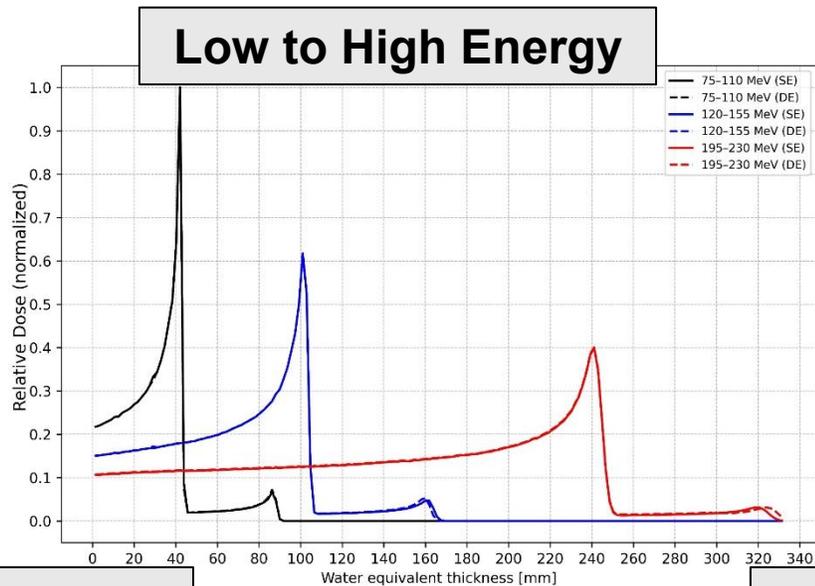
3. Multi energy proton extraction for range probing



4. Integration of pCT detector to the upright PT facility



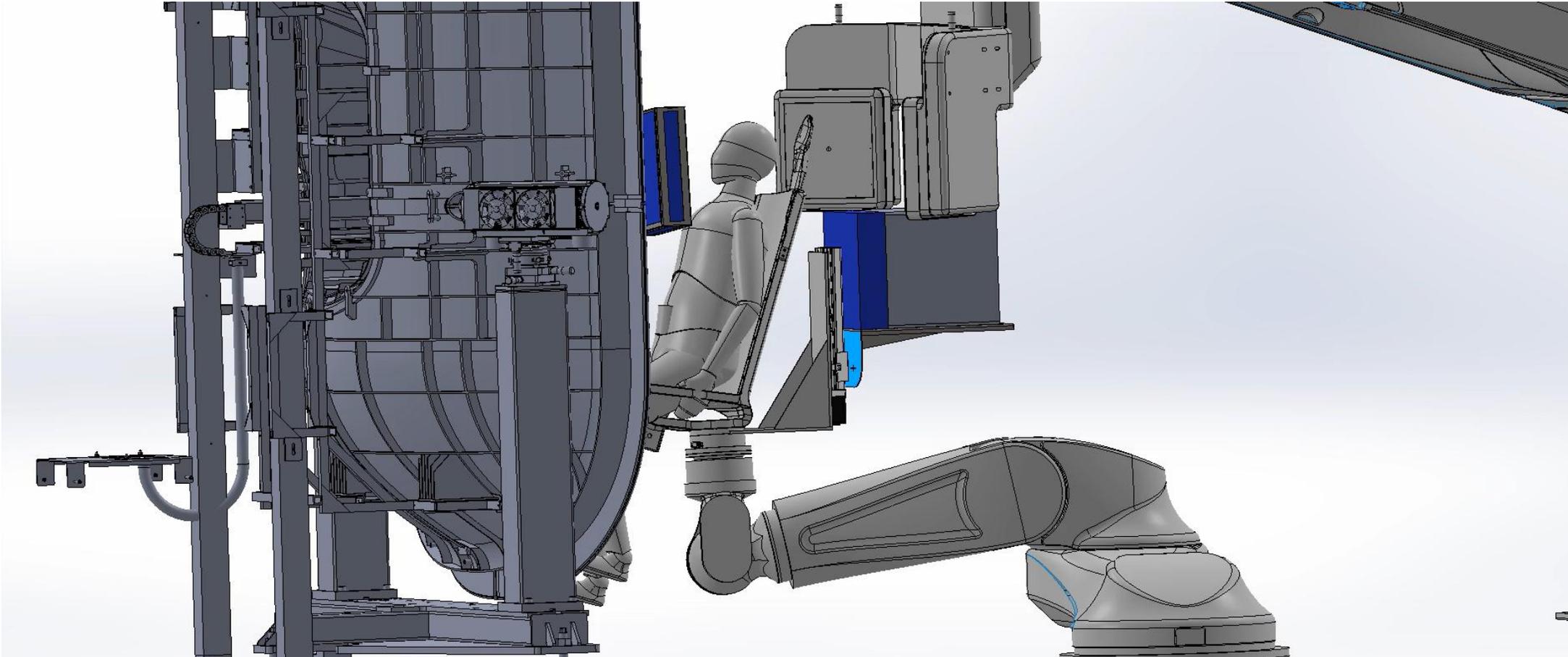
Multi energy extraction for range probing



Pryanichnikov AA et al.
arxiv.org/abs/2506.19736

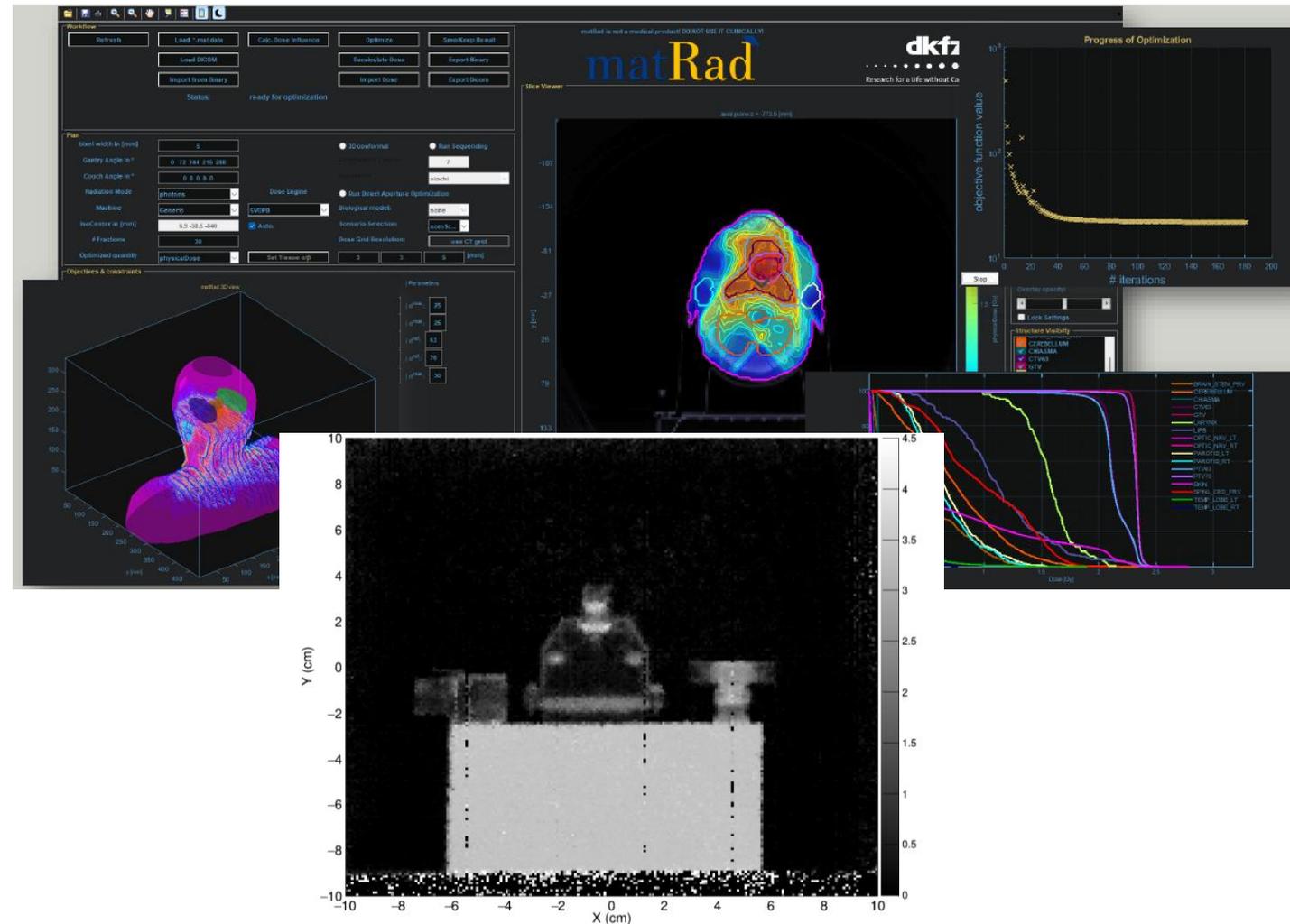


Integration of pCT detector to the upright PT facility



Outlook

- Developed a framework in matRad to calculate and simulate mixed beam treatment plans and corresponding radiographs
- The mixed carbon-helium beam method has a high sensitivity to WET changes and can be used for patient positioning and motioning of anatomical changes during the therapy delivery
- Experimental image had spatial resolution of 1 lp/mm for helium and 0.5 lp/mm for proton beams in single-plane configurations for simple line phantoms
- The WET value accuracy for Gammex inserts was better than 2 mm for single-energy operation
- Operating with a single tracking plane shows promising results for both proton and helium imaging and future integration into particle therapy facilities



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Anahita Bakhtiari Moghaddam, MSc
Niklas Wahl, PhD
Prof. Oliver Jäkel, PhD
Prof. Joao Seco, PhD

IBT KIT



Prof. Maria Francesca Spadea, PhD



HIT

Stephan Brons, PhD
Eike Feldmeier, PhD
Timo Strecker, MSc



Hadassah

Jon Feldman, PhD
Yair Hillman, MSc



ProtonVDA

Ethan DeJongh, MSc
Victor Rykalin, MSc
Fritz DeJongh, PhD



P-Cure

Dmitry Schwartz, PhD
Shimshon Winograd, MSc



Karlsruher Institut für Technologie



Thank you!

Alexander Pryanichnikov, PhD

alexander.pryanichnikov@kit.edu

alexander.pryanichnikov@dkfz-heidelberg.de

dkfz.

GERMAN
CANCER RESEARCH CENTER
IN THE HELMHOLTZ ASSOCIATION



Research for a Life without Cancer